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F/A-18E/F Catapult Minimum End Airspeed Testing

Michael M. Wallace
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Michael M. Wallace entitled "F/A-18E/F Catapult Minimum End Airspeed Testing." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Frank Collins, Major Professor

We have read this thesis and recommend its acceptance:

Ralph Kimberlin, George Garrison

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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F/A-18E/F CATAPULT MINIMUM END AIRSPEED TESTING

A Thesis
Presented for the
Master of Science Degree

The University of Tennessee, Knoxville

Michael M. Wallace
December 2002

Dedication

This thesis is dedicated to my wife Deidre and daughters Morgan and Madison without whose love and support I could not have accomplished this testing and thesis.

Acknowledgements

I wish to express my sincere gratitude to all those who assisted me during the preparation of this thesis. I thank all the members of the F/A-18E/F Integrated Test Team, a combined U.S. Navy and Boeing team, that enabled this testing to occur in a most highly professional manner. I extend my highest gratitude to Mr. Howard Gofus who acted in the finest fashion as the Test Conductor during the tests. I am eternally grateful to Mr. Charles Trost, Mr. John Hagan, Mr. Mark Swierczek, and Mr. Henry Melton, who each provided extensive amounts of data and information regarding the aircraft and the test evolution. I thank Dr. Collins for guiding me through the thesis process. I thank Dr. Kimberlin and Dr. Garrison for serving on my committee.

Abstract

The F/A-18E/F Super Hornet is the result of major upgrades to previous series of F/A-18 Hornet aircraft (F/A-18A/B/C/D). These upgrades resulted in an airplane requiring a complete Engineering and Manufacturing Development (EMD) phase. Catapult minimum end airspeed tests took place near the end of the three and a half year EMD program to provide data for the Aircraft Launch Bulletin for Operational Evaluation and fleet operations. The tests had occurred on average only every six years for any type of aircraft and 10-15 years for the same model of aircraft in the last 30 years.

The objective of this thesis was to document, for future testers and other interested parties, the issues, preparation, method, and results of the F/A-18E/F catapult minimum end airspeed flight tests. The tests occurred during Follow-On Sea Trials aboard the USS HARRY S. TRUMAN (CVN 75) between March 3 and 12, 1999. Seventeen launches were conducted with aircraft F1 and F2 in FULL flaps configuration at four gross weights, two in full non-afterburner thrust and two in full afterburner thrust.

Results showed that the F/A-18E/F met the Specification for launch from the decks of existing U.S. Navy aircraft carriers. The non-afterburner launches above 58,000 pounds were limited by longitudinal acceleration. The afterburner launches up to the maximum gross weight of 66,000 pounds were limited by 10 feet sink-off-of-the-bow.

The opinions, analysis and conclusions expressed in this thesis are solely those of the author and have not been officially approved by the Department of the Navy, Naval Air Systems Command, or The Boeing Company.

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List of Abbreviations

ABLIM	Afterburner Limiter
a/g	Longitudinal Acceleration ratio – N_x/g
ALB	Aircraft Launch Bulletin
AOA	Angle of attack
AVDAU	Avionics Data Acquisition Unit
CAIS	Common Airborne Instrumentation System
CG	Center of gravity
$C_{L\ max}$	Maximum coefficient of lift
CMEA	Catapult minimum end airspeed
CSV	Capacity Selector Valve
CVG	Compressor Variable Geometry
deg	degree
EMD	Engineering and Manufacturing Development
EFT	External Fuel Tank
FADEC	Full Authority Digital Engine Control
FCC	Flight Control Computer
FCS	Flight Control System
FOST	Follow-On Sea Trials
g	Gravitational acceleration – approximately 32.174 ft/second^2

GW	Gross weight
IST	Initial Sea Trials
JBD	Jet Blast Deflector
KEAS	knots equivalent airspeed (Nm/hr)
kt	knot (Nm/hr)
lb	pound force
LEF	Leading Edge Flap
LEX	Leading Edge Extension
MAX	Maximum Rated Thrust (Full Afterburner)
MBPS	Megabits per second
MFHS	Manned Flight Hardware Simulator
MFS	Manned Flight Simulator
MODSDF	Modular Six Degree of Freedom
MUX	Multiplexing
MIL	Military Rated Thrust (Full Non-Afterburning)
NATOPS	Naval Air Training and Operating Procedures Standardization
NFLIR	Navigation Forward Looking Infra-Red Pod
N_x	Longitudinal acceleration (ft/sec^2 or factor of g)
OPEVAL	Operational Evaluation
OR	Operational Requirements
psig	pounds per square inch gage

RDR ATK	RADAR Attack display
SOB	Sink-off-the-bow
sec	second
TECHEVAL	Technical Evaluation
TEF	Trailing Edge Flap
TFLIR	Targeting Forward Looking Infra-Red Pod
TWD	Test Work Description
V_{MC}	Single engine dynamic minimum control speed
WOD	Wind-over-the-deck

Chapter I

Introduction

Background

The prevalent method of launching modern naval airplanes from the decks of aircraft carriers is with the assistance of a catapult. All shipboard aircraft not capable of independently achieving flyaway airspeed prior to leaving the deck of the ship require energy to be imparted to the airplane from the catapult. The steam-powered catapult is currently used for this purpose on all U. S. aircraft carriers. Other catapult designs are under development including electrically powered magnetic catapults for use on future aircraft carriers (Erwin, 2001), however, the principle for launch is the same. The catapult force is transferred through a tow bar or launch bar to achieve the desired acceleration and ultimately flying airspeed. Some wind-over-deck (WOD) may also be required at higher gross weights due to limitations of the catapult or airplane structure.

During the development of catapult launched naval airplanes, the catapult minimum end airspeed (CMEA) must be determined for the gross weight (GW) envelope of the airplane. The absolute catapult minimum end airspeed is defined and explained in the Carrier Suitability Flight Test Manual as,

> the catapult equivalent end speed achieved at the bow of the carrier below which the airplane cannot maintain itself in the air. Although it would be desirable to obtain this absolute minimum airspeed, the minimum end airspeed established is a compromise between the absolute minimum and a higher value which must be accepted because of variations in catapult performance, variable WOD and other safety considerations (SA FTM-01, 1993).

The catapult minimum end airspeed is as close as safely possible to the absolute catapult minimum end airspeed. The CMEA is the airspeed value that can be safely tested aboard an aircraft carrier. The results of the tests provide the catapult operators the Aircraft Launch Bulletins (ALB). The ALB lists a setting for the catapult at a given gross weight and WOD condition for a particular airplane. Airplanes under normal operational conditions are launched with 10 to 15 knots excess airspeed above the published minimum end airspeed to account for variations in catapult performance, wind gusts, and to provide a margin of safety in the event of an aircraft emergency. The benefits of determining the lowest speed acceptable to launch an airplane is fourfold as it:

a. Decreases the WOD requirement for launch, thereby increasing the operational capability of the carrier and airplane.

b. Decreases the loads imposed on the airplane by the catapult, thereby increasing the fatigue life of the airplane.

c. Decreases the amount of energy the catapult must impart to the airplane, thereby conserving carrier fuel and water.

d. Decreases the ship's speed resulting in a significant decrease in fuel consumption.

(SA FTM-01, 1993)

Lower ship's speed is also desirable in confined waters to reduce the distance traveled during launch. Aircraft carriers usually launch 15-30 aircraft each launch at a rate of about one aircraft per minute during cyclic operations. If significant WOD is required for launch in low natural wind conditions, the ship may travel a significant distance in 15-30 minutes.

The relationships between the factors affecting catapult minimum end airspeed are shown in Figure 1. Launch airspeed increases linearly with increasing gross weight. Limit catapult capacity is a finite function and provides high catapult end airspeeds at low GW and visa versa. The maximum gross weight, the limit tow bar load, and the limit longitudinal acceleration limit the airplane envelope. Wind-over-deck is the difference between the minimum end airspeed and the launching envelope at a given gross weight.

The F/A-18E/F Super Hornet was procured as an enhancement to the F/A-18A/B/C/D Hornet and an inventory replacement for the F-14 Tomcat. The McDonnell-Douglas F/A-18 Hornet was designed as a carrier-based dual role aircraft in the 1970's as a derivative of the Northrup YF-17 (Kelly, 1990). The Hornet replaced McDonnell-Douglas F-4 Phantom fighter and the LTV A-7 Corsair II attack airplanes beginning in 1983. The Hornet demonstrated the ability to execute both fighter and attack missions in actual combat in Libya, the Gulf War, Bosnia-Herzegovina/Kosovo, and most recently Afghanistan, but had some limitations including combat radius, endurance, carrier landing payload or "bring back", and survivability against modern surface-to-air and air-

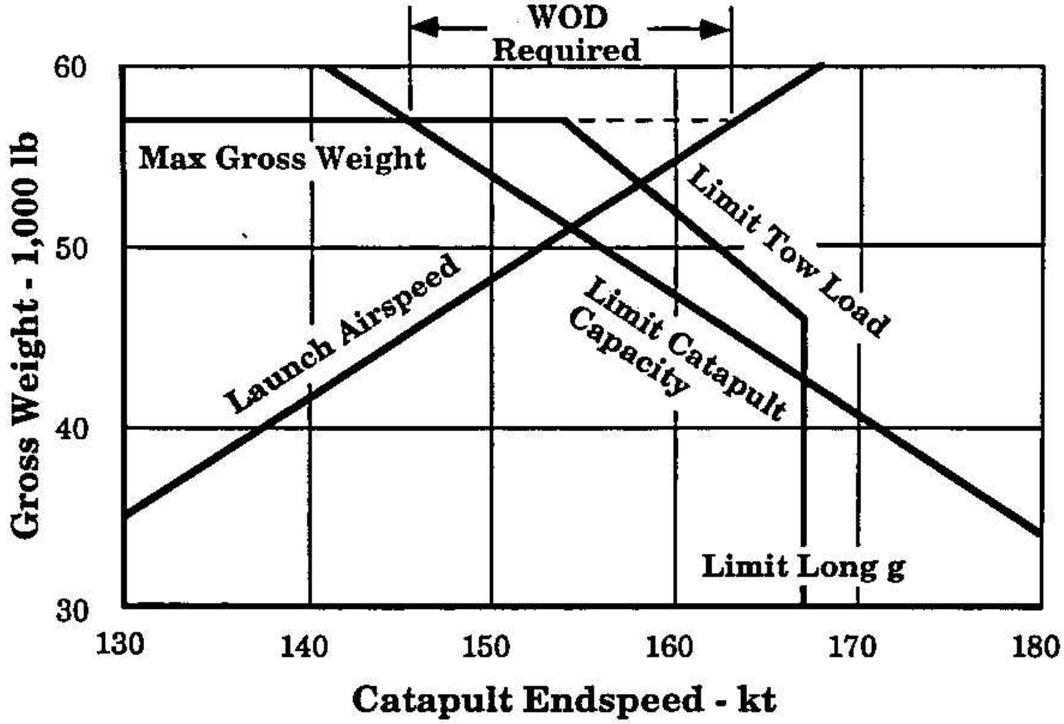


Figure 1. Typical Airplane Launch Conditions

Source: *Carrier Suitability Testing Manual.* SA FTM-01. Patuxent River, Maryland: Naval Air Warfare Center Aircraft Division, Naval Strike Aircraft Test Squadron, November 1993, pp. 5-24.

to-air threats. Additionally, it became evident the Hornet would consume all available remaining space, cooling, and power surpluses for the addition of new technology or "growth" capability somewhere near the end of the 20th century. Although the Hornet was planned to be in service until 2015, there could not be any significant weapon system hardware upgrades for the remaining years of aircraft life.

Proposing a new type of aircraft was unlikely to win Congressional support and funding due to fiscal constraints and the political backlash related to the cancellation of the A-12 Avenger II program. Recognized deficiencies with the F/A-18C/D gave rise in 1991 to Navy Operational Requirements (OR) for an F/A-18E/F upgrade (Coyle, 2000). The leadership of the Navy proposed an enhancement of an existing, proven airplane to ease the battle to win political support. The F/A-18E/F Super Hornet was proposed as an inventory replacement for the aging F-14 Tomcat, to complement the F/A-18 Hornet, and to correct the limitations of the Hornet.

Like the Hornet, the F/A-18E/F Super Hornet was designed as a carrier-based, multi-mission, strike fighter airplane. The Super Hornet was initially designed and built by McDonnell-Douglas. The Boeing Company purchased McDonnell-Douglas in 1998 and absorbed the F/A-18E/F Super Hornet program.

The Navy's Operational Requirement stated that the number one priority was increased internal fuel for added range and endurance. Three additional principal improvements over the existing F/A-18C/D were defined as requirements in the F/A-18E/F Upgrade; increased mission radius/payload flexibility, increased carrier recovery payload, and improved survivability/reduced vulnerability. It also identified required improvements in several other areas. These included combat performance (turn rate, climb rate, and acceleration compared to the Lot XII F/A-18C/D); and growth capability (for general avionics, electrical, environmental control system, flight control, and hydromechanical systems) to support future improvements. While the 1991 OR required both a single-seat F/A-18E and a two-seat version F/A-18F, originally the two-seat version was envisioned to serve only as a trainer. Subsequently, the Navy directed that the F/A-18F would become the inventory replacement for the F-14 Tomcat (Coyle, 2000).

The significant carrier suitability events that occur during the Engineering, Manufacturing, and Development (EMD) phase are the Initial Sea Trials (IST), Technical Evaluation (TECHEVAL) or Follow-On Sea Trials (FOST). The Operational Evaluation (OPEVAL) is immediately subsequent to the EMD phase. The Initial Sea-Trials usually occur approximately one year after the first flight in the EMD phase (Zirkel, et al, 1997). The F/A-18E/F was no exception, with the Initial Sea Trials occurring in January 1997, one year and one month following the first flight of F/A-18E/F. Follow-On Sea Trials or TECHEVAL is normally scheduled to occur approximately two years after the Initial Sea Trials near the end of EMD just prior to OPEVAL.

The EMD phase took place from November 1995 through April 1999. The Super Hornet was initially tested at sea during Initial Sea Trials aboard USS JOHN C. STENNIS (CVN 74) in January 1997. During the Initial Sea Trials, the F/A-18E/F without external wing stores demonstrated basic carrier compatibility. Catapult launches utilized excess end airspeed of 15 knots or greater above the predicted minimum end airspeed to evaluated center of gravity (CG) and trimming effects on launch (Gurney, 1997). CMEA tests are generally not performed during the Initial Sea Trials due to the developmental immaturity of the aircraft (SA FTM-01, 1993).

The catapult minimum end airspeed tests were part of the Carrier Suitability portion of the EMD program. One of the final requirements during the EMD phase was to determine the Aircraft Launch Bulletins for catapult launch from all U. S. Navy aircraft carrier decks. The catapult minimum end airspeed tests occurred during the Follow-On Sea Trials (FOST) conducted aboard USS HARRY S. TRUMAN from March 4-12, 1999. Prior to the F/A-18E/F program, the Follow-On Sea Trials were known as the Technical Evaluation (TECHEVAL). The Follow-On Sea Trials were the final developmental tests for the F/A-18E/F aboard an aircraft carrier prior to the OPEVAL. The objective of FOST was to provide an acceptable launch and recovery envelope for use during OPEVAL and if validated for fleet operational use.

A simplified overview of the test is launching the airplane from an aircraft carrier catapult at incrementally slower airspeeds until determination of the catapult minimum end airspeed. The minimum end airspeed is defined by certain criteria, primarily downward vertical displacement of the CG below the static plane of the carrier flight deck, referred to as "sink off bow" (SOB), longitudinal acceleration, and pilot comfort level based on flying qualities.

This type of testing occurred with decreasing frequency over the last 25 years due to the significant reduction in procurement of new models of naval carrier airplanes and upgrades to engines. On average, during the last 25 years, catapult minimum end airspeed flight testing has occurred only once every 6 years for models of all U. S. Navy airplane types and 15-20 years for the same model. Figure 2 depicts the trend of this type of testing. Although Figure 2 depicts Initial Sea Trial trends, catapult minimum end airspeed testing occurred at the same frequency only shifted two years later. The author's experience was that few key personnel, if any, involved in catapult minimum end airspeed testing had previous experience with this specialized type of testing, including the author and the other pilots involved in the test. Therefore, test procedure manuals, literature, previous test plans and reports were heavily relied upon to ensure the safe completion of the testing.

This thesis is intended to document, for future testers and other interested parties, the issues, preparation, method, and results of the F/A-18E/F catapult minimum end airspeed flight tests. The objective was to provide a comprehensive point of reference and insight into catapult minimum end airspeed flight testing with particular emphasis on the F/A-18E/F Super Hornet.

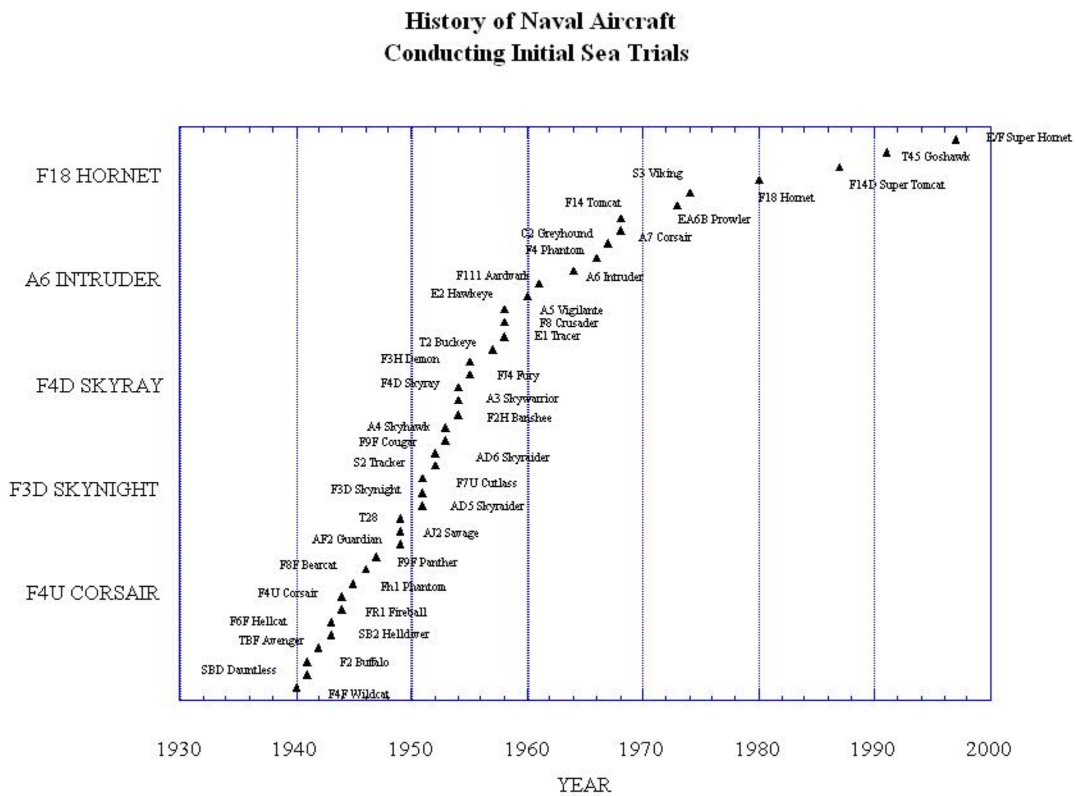


Figure 2. Frequency Trend of Sea Trial Testing

Source: Tribino, Michael. "F/A-18E/F Initial Sea Trials Briefing." Patuxent River, Maryland: Briefing presented December 1996.

The unique aspects of this flight test were the decision to use 10 ft SOB instead of 20 ft SOB as the endpoint criteria, the extensive simulation of airplane performance and possible degraded failure modes, the implementation of the Afterburner Limiter (ABLIM) function to eliminate compressor stalls due to hot gas reingestion, and the risk mitigation for engine stall during the CMEA tests.

Chapter II

Scope of Thesis

This thesis focuses on the catapult minimum end airspeed flight tests on March 5, 9, and 11, 1999 that occurred during the Follow-On Sea Trials aboard USS HARRY S. TRUMAN (CVN 75) on the Atlantic Ocean off the east coast of the United States. The CMEA tests consisted of 17 total launches at four separate gross weights. Prerequisite testing that occurred prior to the CMEA test is mentioned as it pertained to the preparation for the CMEA tests. The author piloted the 63,000 lb MIL tests and the 66,000 lb MAX tests.

Test Articles

Two prototype F/A-18F models were used for the tests. The Boeing designation for the test articles was F1 and F2 as the airplanes were the first and second two-seat Super Hornet prototypes manufactured for the EMD program. The Navy Bureau Numbers assigned to the airplanes were 165166 and 165170 respectively. While both airplanes were highly instrumented for flight test, F1 and F2 were considered to be production representative and equivalent in performance to single seat F/A-18E versions within the scope of this test.

Test Configurations and Loadings

The aircraft configuration for the CMEA test was flaps FULL. Engine thrust settings are described in two ways for this test. Military Rated Thrust (MIL) is full throttle non-afterburner thrust, also known as Intermediate Rated Thrust. Maximum Rated Thrust (MAX) is full throttle with full afterburner thrust selected. An Afterburner Limiter (ABLIM) system was engaged for all MAX power launches to initially limit the afterburner thrust increment to half. Engine thrust for launch was set at MIL or MAX depending on the gross weight. Landing gear remained in the extended position until the completion of the test point. Takeoff trim was set to optimize rotation pitch rates and peak angle of attack (AOA). The target pitch rate was 10 to 12 degrees per second and the maximum peak AOA was 15 degrees. The Flight Control Computer (FCC) Operational Flight Program Version 7.3 was loaded in both FCCs. Both Mission Computers were loaded with Operational Flight Program 11E-007.

The aircraft was launched at four gross weights, approximately 58,000 and 63,000 pounds for MIL, and approximately 61,000 and the maximum allowable gross weight of 66,000 pounds at MAX, to determine the ALB for the entire gross weight envelope. The two points at each thrust setting formed two lines that defined the upper gross weight launch minimum end airspeed. The relationship between minimum end airspeed and gross weight is linear as depicted in Figure 3. Launching below 58,000 pounds GW was not required because the speed that defined the predicted minimum end airspeed at

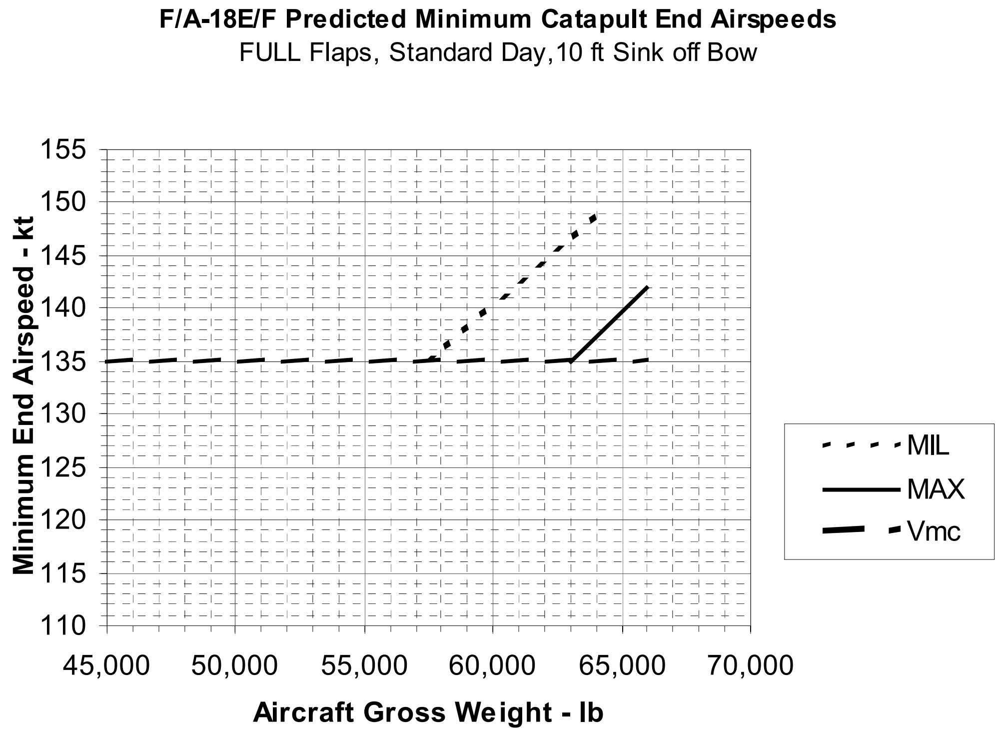


Figure 3. F/A-18E/F Predicted Minimum End Airspeed vs. Airplane Gross Weight

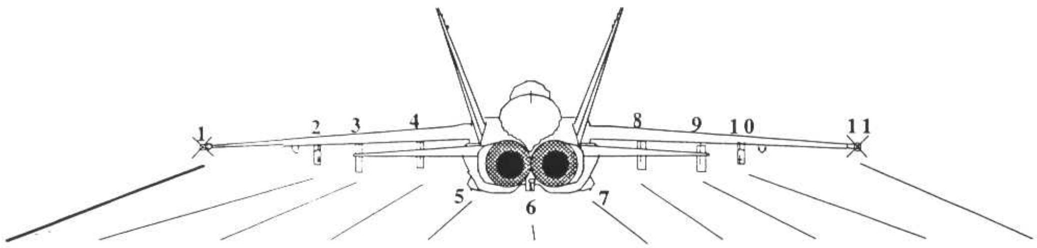
Adapted from *Follow-On Sea Trials.* Test Work Description FMV08.07-004, FA-18E/F Integrated Test Team, NAS Patuxent River, MD, February 1999.

58,000 pounds GW was determined by the symmetric single engine dynamic minimum controllable speed (V_{MC}) of 135 knots.

FOST was the first F/A-18E/F evaluation aboard an aircraft carrier with external wing stores cleared for launch and recovery. Achieving the gross weights desired for the launch testing required several external stores configurations. Figure 4 lists the loadings used for the CMEA tests. In order to achieve the maximum allowable gross weight, the heaviest configuration, Loading E, included three external fuel tanks (EFT) containing 480 gallons of JP-5 jet fuel (approximately 3260 pounds) each. Loading E also included under-wing weapon pylons with six inert MK-83 bombs weighing 985 lbs each, a Targeting Forward Looking Infrared (TFLIR) pod, a Navigation FLIR pod (NFLIR), and two captive AIM-9 Sidewinder training missiles (CATM-9) on the wingtip stations. Lighter gross weights, depicted in Figure 4 as Loading C and D, were achieved by reducing the number of external stores and internal fuel load.

The abbreviations in Figure 4 are explained here for clarity; LAU-127- wingtip missile launcher; SUU-80- suspension unit, under wing (low drag pylon for stations 2 and 10); SUU-79- suspension unit, under wing (pylon for stations 3, 4, 8, and 9); SUU-78 suspension unit, under fuselage (station 6 pylon); Sen Cvr - Sensor Cover (permitted the attachment of TFLIR and NFLIR pods to stations 5 and 7); 480 EFT- 480 gallon external fuel tank; MK-83- 985 lb inert practice bomb with conical fin.

TEST LOADINGS



Ltip Sta 1	Outbd Sta 2	Midbd Sta 3	Inbd Sta 4	Lfus Sta 5	Cl Sta 6	Rfus Sta 7	Inbd Sta 8	Midbd Sta 9	Outbd Sta 10	Rtip Sta 11

Loading C - 60Klb minimum

LAU-127 CATM-9	SUU-8 MK-83	SUU-79 MK-83	SUU-79 480 EFT Full	Sen Cvr TFLIR	SUU-78	Sen Cvr NFLIR	SUU-79 480 EFT Full	SUU-79 MK-83	SUU-80 MK-83	LAU-127 CATM-9

Loading D - 58Klb minimum

LAU-127 CATM-9	SUU-80 MK-83	SUU-79 MK-83	SUU-79 480 EFT Full	Sen Cvr TFLIR	SUU-78 MK-83	Sen Cvr NFLIR	SUU-79 480 EFT Full	SUU-79 MK-83	SUU-80 MK-83	LAU-127 CATM-9

Loading E - 66Klb/63Klb minimum

LAU-127 CATM-9	SUU-80 MK-83	SUU-79 CVER 2MK-83	SUU-79 480 EFT Full	Sen Cvr TFLIR	SUU-78 480 EFT Full	Sen Cvr NFLIR	SUU-79 480 EFT Full	SUU-79 CVER 2MK-83	SUU-80 MK-83	LAU-127 CATM-9

Loading I – Recovery (Loading C & D download)

LAU-127 CATM-9	SUU-80	SUU-79 MK-83	SUU-79 480 EFT Empty	Sen Cvr TFLIR	SUU-78	Sen Cvr NFLIR	SUU-79 480 EFT Empty	SUU-79 MK-83	SUU-80	LAU-127 CATM-9

Loading J – Recovery (Loading E download)

LAU-127 CATM-9	SUU-80 MK-83	SUU-79 CVER	SUU-79 480 EFT Empty	Sen Cvr TFLIR	SUU-78 480 EFT Empty	Sen Cvr NFLIR	SUU-79 480 EFT Empty	SUU-79 CVER	SUU-80 MK-83	LAU-127 CATM-9

Figure 4. Test Loadings

Source: *Follow-On Sea Trials.* Test Work Description FMV08.07-004, FA-18E/F Integrated Test Team, NAS Patuxent River, MD, February 1999.

The basic aircraft weight is defined as the aircraft weight without fuel, external stores, and crew. The basic aircraft weight for F1 and F2 was 32,841 and 31,880 pounds respectively (Form F, 1999). The fuel load during the launches was up to 23,000 lb. The maximum recovery gross weight for the airplane was 44,000 lb. To achieve the maximum recovery gross weight expeditiously, additional fuel was dumped and some of the MK-83 inert bombs were jettisoned from the airplane after each launch. The recovery loadings were Loading I (Loading C and D download) and Loading J (Loading E download). Modifying external tanks to hold water that would dump after launch was deemed too expensive compared to the cost of dumping fuel.

CVN 75 Catapult and Jet Blast Deflector Configuration

USS HARRY S. TRUMAN was configured with C13-2 catapults and MK 7 Mod 0 Jet Blast Deflectors (JBD). The bow catapults, Number 1 and 2, were used for the tests. The catapults were not aligned with ship centerline. The JBDs were positioned perpendicular to ship's centerline resulting in a 91° 53' 39" and 95° 13' 25" clockwise angle relative to catapult track No. 1 and 2 respectively. The JBD centerline was positioned at 57 feet 9 inches and 67 ft 4 inches respectively behind catapult track No. 1 and No. 2 (Zirkel, et al, 1997).

Author's Role

The author was assigned to the F/A-18E/F Integrated Test Team during EMD in November 1999 and served as the F/A-18E/F Lead Carrier Suitability Test Pilot from June 1998 through June 1999. The author was deeply involved in planning the testing, development of test methods, emergency procedures, simulator evaluations, and all prerequisite testing and planning. The author piloted aircraft F1 for the 63,000 lb GW MIL power and the maximum allowable gross weight 66,000 lb MAX thrust tests. The opinions, analysis and conclusions expressed in this thesis are solely those of the author and are not officially approved or endorsed by the Department of Defense, the Department of the Navy, the Naval Air Systems Command, or The Boeing Company.

Chapter III

Description of FA-18E/F Super Hornet Airplane

Basic airplane overview

The F/A-18E/F Super Hornet is a twin engine, digital fly-by-wire, carrier based multi-mission, strike fighter aircraft designed and built by The Boeing Company. The airplane is produced in two versions: the single seat E model and the two-seat F model. The airplane features a variable camber wing with leading edge flaps (LEF) and trailing edge flaps (TEF), ailerons, a highly swept leading edge extension (LEX), twin vertical stabilizers canted outboard 20 degrees from the vertical axis with twin rudders, and dual horizontal stabilizers capable of symmetric and differential actuation. The airplane wing incorporated a porous fairing above the wing fold designated 18-17PT2.

The flight control system (FCS) is an enhanced version of the existing F/A-18 Hornet four channel fly-by-wire system, designed to increase reliability and maintainability without compromising flying qualities. The enhanced FCS has additional electrical system redundancy, and eliminates the mechanical reversion mode incorporated in the F/A-18 Hornet FCS. The FCS is actuated by a dual-pressure (3000 or 5000 psig) hydraulic system consisting of two independent systems with two circuits each.

The avionics system of the airplane incorporated six MIL-STD 1553 Multiplexing (MUX) busses for the transfer of data between onboard computers, control of subsystems, and redundancy management. The instrumentation system was capable of retrieving data directly from four of the six 1553 MUX busses.

A depiction of the airplane along with approximate dimensions is presented in Figure 5. The overall dimensions for the F/A-18E and F are identical. Additional dimensional data and specifications are presented in Table 1.

Flight Control Description for Catapult Flyaway

The airplane launches from the catapult near 0 degrees AOA. The flight control algorithm for the longitudinal axis was designed for hands free catapult launch. The design incorporated an AOA capture scheme for rotation during catapult launch. The design capture AOA was 12 degrees. The longitudinal trim setting determined the pitch rate to achieve the capture AOA. The desired pitch rate was 10 to 12 degrees per second to optimize the transition to flight while maintaining comfortable pitch rates for the pilot to avoid possible disorientation during night catapult launches. The guideline for the maximum pitch rate that will maintain acceptable pilot comfort levels is 12 degrees per second (SA FTM-01, 1993; Bowes, 1972).

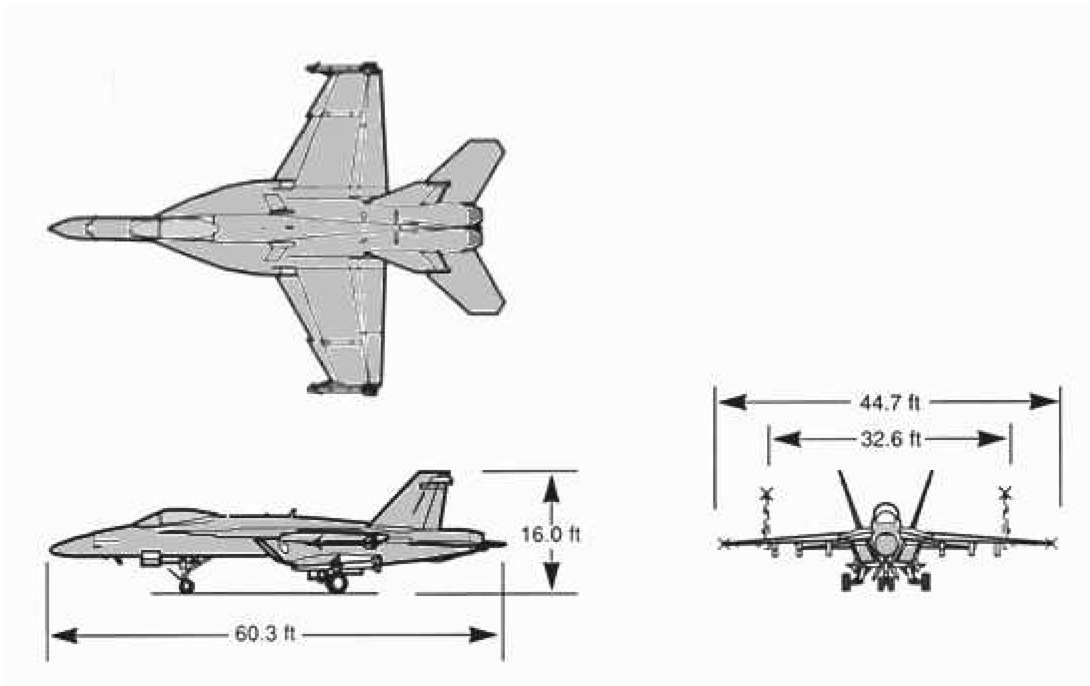


Figure 5. F/A-18E/F Three View with Dimensions (F/A-18E Depicted)

Adapted from *F/A-18E/F Preliminary Naval Air Training and Operating Procedures Standardization* (NATOPS) Flight Manual. Patuxent River, Maryland: Department of the Navy, Naval Air Systems Command, March 1999.

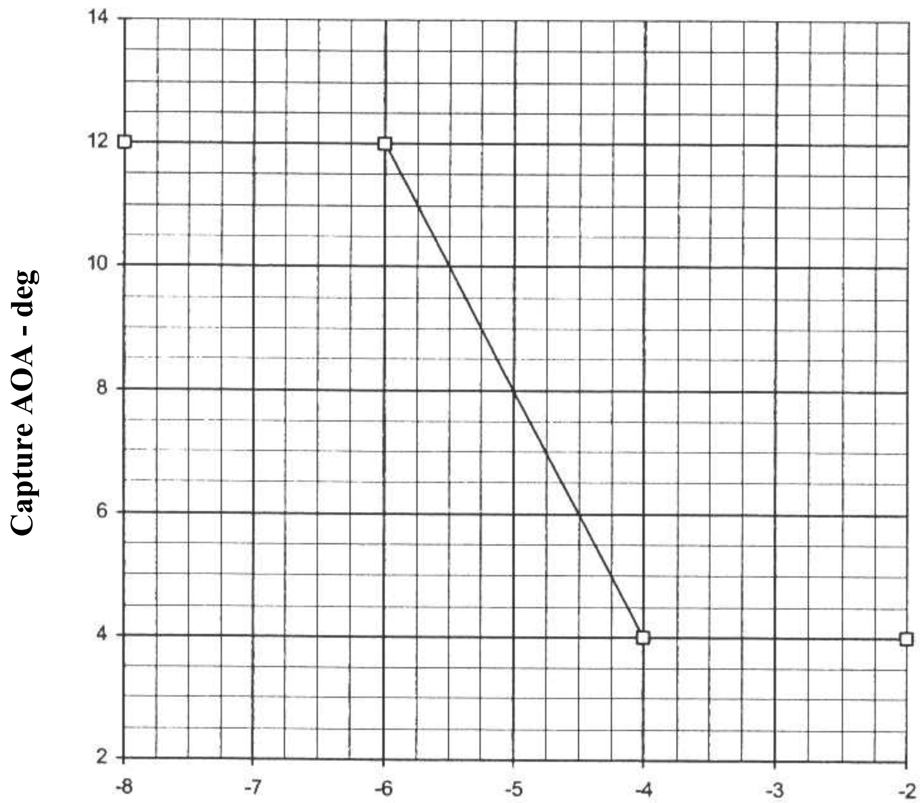
Table 1. General F/A-18E/F Specifications

Specification	Data
Internal Fuel Capacity (F model) JP-5	13,552 lb/1993 gallons
Maximum Allowable Carrier or Field Takeoff Weight	66,000 lb
Maximum Carrier Landing Weight	44,000 lb
Wing Airfoil Section	NACA 65A
Wing Area	500 ft^2
Wing Dihedral Angle	-3 degrees
Wing Incidence	0 degrees
Wing Twist Root to Tip	0 degrees
Aspect Ratio	3.5
LEX Area	75 ft^2
Horizontal Tail Area	120 ft^2
Horizontal Tail Dihedral Angle	-3 degrees
Vertical Tail Area	120 ft^2

Source: *Detail Specification for Model F/A-18E/F Aircraft Weapons Systems.* SD-565-3-1 Volume I. Washington, District of Columbia: Department of the Navy, Naval Air Systems Command, September 1995.

The FCS accomplished a hands free catapult launch primarily by AOA and pitch rate feedback. The angle of attack trim reference, or pitch trim integrator output, is scheduled as a function of pitch integrator output to permit a hands free catapult takeoff. The pitch trim integrator output gets set to the takeoff reference value if the takeoff trim switch is pressed or the pitch trim switch on the control stick is activated with weight on wheels (Demand, 2000).

The capture AOA schedule is related to longitudinal trim setting as depicted in Figure 6. There is a rapid transition in AOA capture from 4 to 12 degrees within the horizontal stabilator trim setting of 4 to 6 degrees trailing edge up respectively. This is to differentiate between field and carrier takeoff. For field takeoff, the longitudinal trim setting is always 4 degrees and the pilot pulls back on the control stick at nose wheel lift off speed to rotate and fly the aircraft away. The field AOA capture is 4 degrees. During catapult launch, the longitudinal trim setting is required to be 6 degrees horizontal tail trailing edge up or greater and the AOA capture therefore 12 degrees AOA. The greater the trim setting at launch, the higher the pitch rate to the capture AOA for a given GW and CG. Setting longitudinal horizontal stabilator trim more trailing edge up from the predicted optimum setting increased the pitch rate once airborne and could result in AOA overshoots greater than 3 degrees. The horizontal stabilator could be trimmed up to a maximum of 24 degrees trailing edge up.



Horizontal Stabilator Trim

Note: Negative values indicate trailing edge up

Figure 6. AOA Trim Reference Schedule

Source: Demand, Ronald P., *F/A-18E/F Flight Control System Design Report, Volume II, Control Law Operation and Mechanization*. Report number MDC 95A0037, Volume II, Revision O. St. Louis, Missouri: July 1995, Revised Feb 2000.

Engines

Two General Electric F414-GE-400 afterburning, low bypass, axial flow, twin spool, seven stage, turbofan engines power the airplane. The F414-GE-400 is a hybrid of the F404-GE-400 series engine that powered the F/A-18 Hornet. Each engine was designed to provide approximately 16,000 lb thrust at MIL and 22,000 lb of thrust at MAX (uninstalled static thrust rating based on sea-level standard atmosphere). A Full Authority Digital Engine Control (FADEC) controlled engine operation. The cockpit throttle levers did not mechanically connect to the FADEC or engine. An electrical signal sent from the throttles to the FADEC represented the requested throttle setting. The FADEC monitored engine operating parameters and flight condition to implement the engine control schedules by modulating the fuel flow and engine geometry for the commanded throttle setting. The FADEC software load for the test was 13E-463.

Afterburner Limiter (ABLIM)

Engine pop stalls while operating in full afterburner with the JBD raised behind the aircraft were noted during JBD compatibility testing at NAES Lakehurst, New Jersey in September 1998. The pop stalls occurred with the airplane nose wheel positioned 57 feet 9 inches forward of the JBD hinge line. The position was known as the "58 foot" position, rounded up from the actual distance. That position represented the launch position on catapult No. 1 and No. 3 on all Nimitz class aircraft carriers (CVN 68 and up). During the JBD compatibility tests, certain conditions resulted in reingestion of hot exhaust gas deflected from the JBD into the engine inlet causing a self-recovering pop stall.

The FADEC software 13E-463 incorporated an ABLIM feature to eliminate the engine pop stalls due to hot gas reingestion. The ABLIM function reduced afterburner thrust to approximately half when the airplane was in position for a catapult launch and then quickly returned the command to full afterburner at the beginning of the catapult stroke. ABLIM reduced the electronic throttle handle angle signal FADEC input to a value for approximately half afterburner when ABLIM was activated by the pilot, the flap switch was either HALF or FULL, and the throttle handle angle exceeded the half afterburner position.

There was great concern among the test team and program leadership regarding the proper operation of ABLIM because of its significant accompanied thrust reduction. This type of thrust modulation during a catapult launch had never been attempted before. In order to satisfy all of the stakeholders, three paths were incorporated into the ABLIM software to ensure the function did not remain activated after the catapult launch. For redundancy, the Flight Control Computer (FCC) portion of the logic had two independent paths, and the mission computer had another, any of which could terminate the ABLIM function and command full afterburner.

The primary path was driven by longitudinal acceleration (N_x). A filtered N_x threshold of 0.4 g (12.9 ft/second^2) was set to command full afterburner after the catapult stroke had begun. That level of acceleration equated to approximately 5 feet of travel on the 309-foot catapult stroke. Once full afterburner was commanded through the longitudinal acceleration path, a 20 second timer prevented the ABLIM function from reducing the engine to half afterburner with full afterburner selected in order to prevent the FCC from reverting to half afterburner following the end of the catapult stroke when the filtered longitudinal acceleration ratio may drop below 0.4 g (Barrett, 2002).

The secondary path in the ABLIM function was the air data path. Full afterburner was commanded when measured airspeed reached 65 knots. Due to lag between actual airspeed and measured airspeed during the catapult launch, actual airspeed could be as high as 80 knots when full afterburner was commanded. The third path was when the weight-off-wheels discrete was sent by the mission computers (Barrett, 2002). The transient from half to full afterburner took approximately 0.5 seconds, therefore in the worst-case scenario, the engines were capable of returning to full afterburner thrust within 1 second of launch. Flight testing of the ABLIM function at a shorebased catapult at NAES Lakehurst, New Jersey demonstrated flawless functionality of ABLIM prior to the shipboard tests.

The six engines utilized for the test were specially prepared to ensure the maximum stall margin for the test. All six engines were rebuilt with recoated compressor cases to minimize compressor clearances and a redesigned number 3 bearings to reduce the damper clearance. The FADEC software for the six engines included ABLIM and a compressor variable geometry “kicker” to increase the engine stall margin during high power transients while the compressor case expanded and the rotating core’s thermal expansion left increased tip to case clearance. The compressor variable geometry "kicker" was activated for 90 seconds at MIL or above with weight-on-wheels. A W-seal between the 7th stage cooling flow and 4th stage turbine guide vane cooling flow was implicated during an engine stall analysis. One of the selected engines had a redesigned W-seal and the five others had low time W-seals that improved engine cooling flow sealing. After all changes were made to the engines, all six engines were tested at NAES Lakehurst, New Jersey in aircraft at the 58-foot position with ABLIM to ensure none would pop stall.

Data System Description

The instrumentation system was configured to support the primary test missions assigned to Fl and F2. The instrumentation system installed in Fl and F2 was the Common Airborne Instrumentation System (CAIS). CAIS was designed to provide a high accuracy, low power, compact data system to meet the rigorous requirements of military aircraft flight testing. CAIS operated at a data bit rate of 15 Megabits per second (Mbps) for analog/digital encoding with processing being accomplished in 5 Mbps sections or "streams" of data. CAIS also incorporated serial 1553 MUX Bus data in both a selected stream format and a MUX-All format. The system was configured to handle three streams of low sample rate analog data (at 5 Mbps each), and four serial streams of 1553 MUX Bus data and MUX-All (all MUX bus traffic). The entire combined Pulse Code Modulated stream was recorded on magnetic tape with a transverse scan digital tape recorder. An S-Band telemetry system was installed providing the capability to encrypt and transmit a subset of the CAIS data (up to 5 Mbps), including digitized pilot's voice (hot mic) and time code. (FOST TWD, 1999)

MUX Bus data was acquired with the CAIS Avionics Data Acquisition Unit (AVDAU), and Bus Interface Module. The AVDAU had the capability to monitor two MUX Busses (Bus 1 & 2) and the integration of the Bus Interface Module added two additional busses (Bus 5 & 6). The AVDAU also had MUX-All capabilities and passed a 4 Mbps bit rate output to the onboard Pulse Code Modulated data combiner (FOST TWD, 1999).

Time correlation was provided with a time code signal from an external time code generator. Time code was embedded in the Pulse Code Modulated stream and utilized by the CAIS AVDAU to generate time tags for selected MUX parameters. Parallel time code was output to the Mission Computer for display on the Heads-Up Display (HUD), Up-Front Control Display (UFCD), Multi-purpose Color Display (MPCD), left and right Multi-functional Display Indicator (MDI) (FOST TWD, 1999).

Control of the instrumentation system was accomplished from the Flight Test Control Panels. The Master Control/Display Panel and the Telemetry Control Panel were located in the cockpit on the right console. The glareshield Panel was located on the left side of the Heads-Up-Display. Instrumentation control functions and displays available to the pilot are depicted in Figure 7.

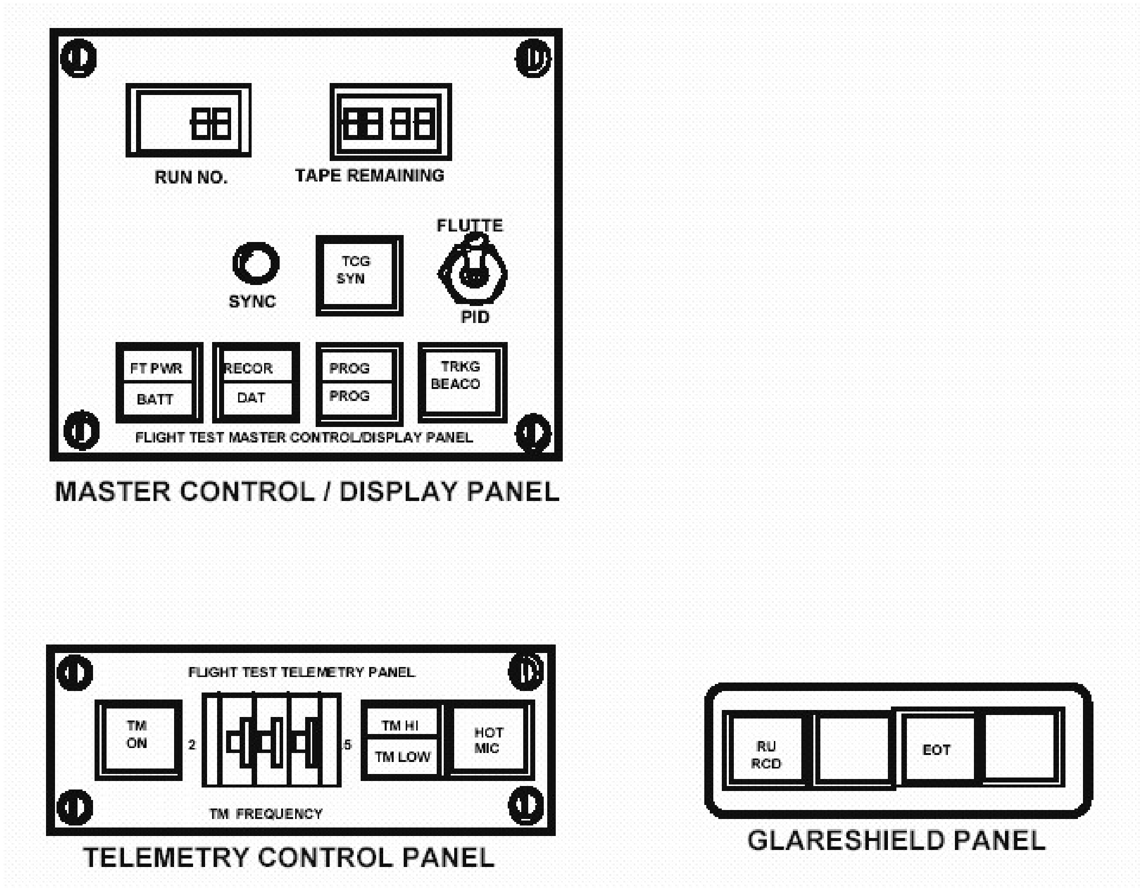


Figure 7. Cockpit Control Panels

Source: *CAIS Core Demonstration Instrumentation Report*. Report number MDC 94A0098, St. Louis Missouri: 1994.

Basic Instrumentation

The Carrier Suitability Test Manual (1993) describes the basic parameters required for analysis of the test as:

- Airspeed
- Altitude
- Angle of Attack
- Pitch Rate
- Roll Attitude
- Rate of Climb
- Longitudinal Control Surface Position
- Engine RPM (each spool)
- Engine Nozzle Total Pressure
- RADAR Altitude

Any significant wave action can make radar altitude unusable for precision SOB measurement. All SOB measurements are normally corrected to aircraft CG. A precise vertical accelerometer integrated twice can be used to determine precise SOB during post flight analysis (Bowes and Stenko, 1972). The F/A-18E/F tests used radar altitude with one foot resolution for real-time assessment and the integral of Inertial Navigation System vertical velocity for post flight data analysis of SOB (Niewald, et al, 1999).

Safety of Test Parameters

A safety of test parameter was required to alert the pilot of failure or impending failure of a critical aircraft system, or any unsafe condition during the test. Telemetry of these parameters was required for the test. Failure of the parameter and all backups prior to launch required maintenance. Loss of the parameter airborne required landing or proceeding with alternate, pre-briefed missions not requiring the failed parameters.

Hundreds of additional parameters were monitored for this test for post flight analysis. The list of the Safety of Test Parameters was as follows:

Angle of Attack, RADAR altitude (CG corrected), Calibrated Airspeed, CG, LEF Position, TEF Position, Lateral Stick Position, Longitudinal Stick Position, Pitch Rate, Pitch Attitude, Roll Angle, Rudder Pedal Force, Left Rudder Position, Right Rudder Position, Left Stabilator Position, Right Stabilator Position, Left Aileron Position, Right Aileron Position, Longitudinal Acceleration (N_x) (FOST TWD, 1999).

Chapter IV

Description of Shipboard Equipment and Instrumentation

Description of Catapult (C13-2)

The catapults used during the test were catapults No. 1 and No. 2 aboard CVN 75. These catapults are located on the bow of the ship on the starboard and port sides respectively. The bow catapults are desired for catapult minimum end airspeed testing due to the undisturbed airstream ahead of the ship. The waist catapults, No. 3 and No. 4, are not desirable for CMEA testing due to the increased potential for free airstream disturbances.

The C13-2 steam powered catapult is a flush deck type system consisting of slotted dual 21-inch diameter power cylinders mounted just below the flight deck. Inside the dual cylinders, connectors that extend through cylinder slots couple two steam pistons. The slots are sealed by a metal sealing strip that allows the pistons to travel along the power cylinders while preventing significant steam pressure from escaping. The tow fitting or shuttle resides above the flight deck attached to the piston connectors through an attachment extending through a 1.5 inch slot extending the length of the catapult between the power cylinders. The aircraft launch bar is seated in the shuttle during the catapult launch and automatically disengages from the shuttle at the end of the power stroke. The C13-2 catapult operates at a maximum steam pressure of 450 psig and maximum steam temperature of 459 deg F (Zirkel, et al, 1997). The general arrangement of the catapult system is shown in Figure 8.

The ship's boilers provide the steam for the catapult. The steam is accumulated in a wet type reservoir. The wet reservoir is filled half full with superheated water and the remaining half with steam. The Capacity Selector Valve (CSV) meters a specific amount of steam from the receiver to the power cylinders based on the catapult operator's setting when the catapult is fired. When the steam pressure drops in the receiver during a launch, the superheated water flashes to steam to maintain a high steam pressure level to the power cylinders. The dual pistons are brought to a stop by a tapered retardation spear mounted on the front of each piston engaging a water brake. The water brake consists of two cylinders kept full of water by a jet-induced vortex. The tapered spear develops high pressure in the water brake that forces water out toward a deflector at the base of the spear. The reversal of momentum at the deflector of the high-pressure water decelerates the piston assembly to a stop in approximately 5 feet. A water brake is depicted in Figure 9. The C13-2 catapult is capable of releasing 75,000,000 foot-pounds of energy (Zirkel, et al, 1997) or 1.01686×10^8 Joules per catapult stroke. The power stroke is 309 ft long.

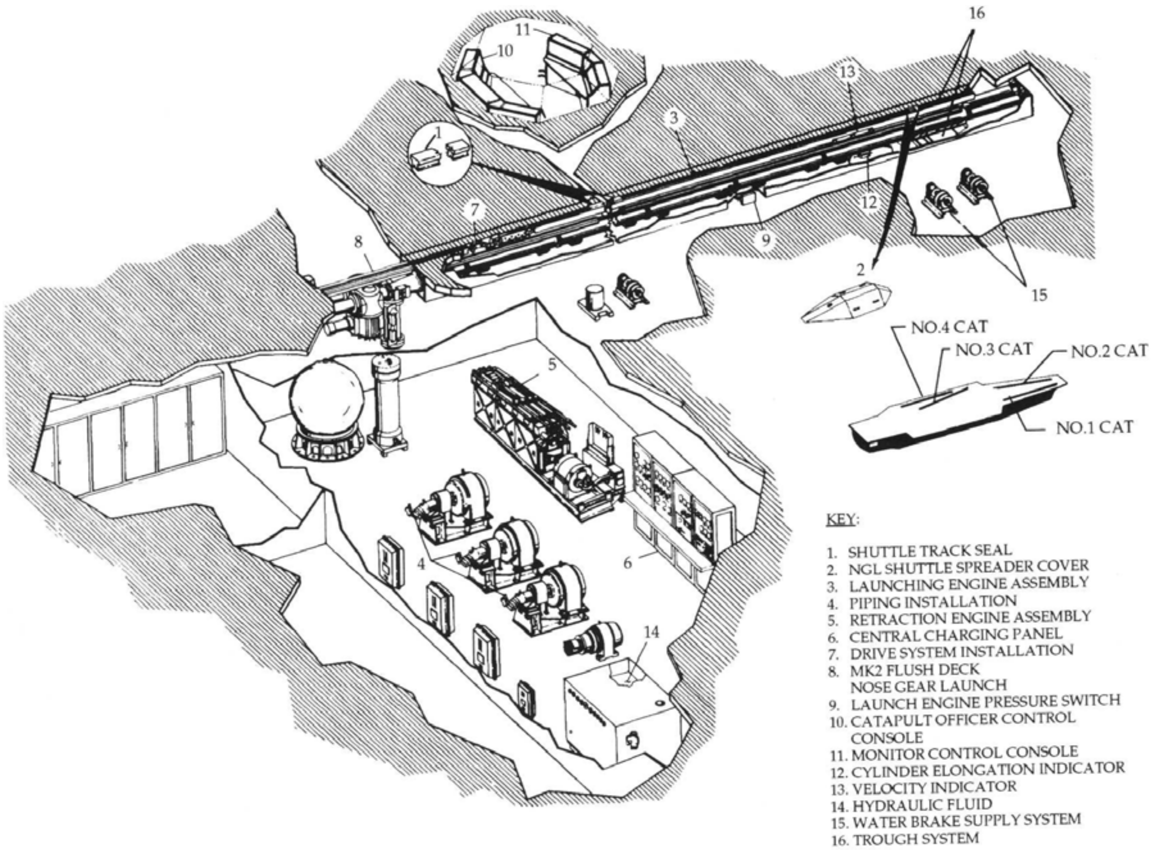


Figure 8. General Catapult Arrangement

Source: Zirkel, John, Kevin Nace, and Chris Ziem. *Aircraft Carrier Reference Data Manual.* Revision D, NAEC-MISC-06900, Lakehurst, New Jersey: Naval Air Warfare Center Aircraft Division, November 1997.

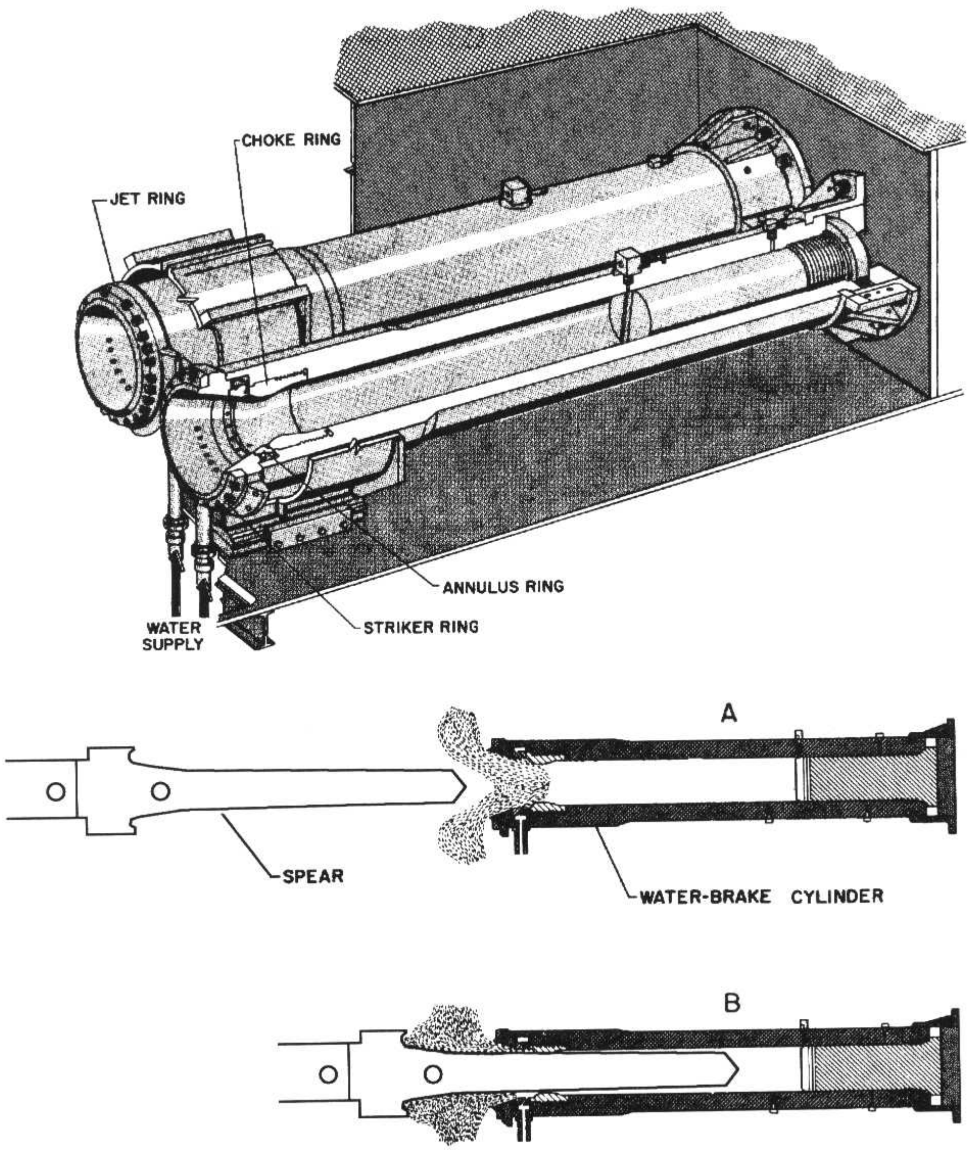


Figure 9. Water Brake

Source: Source: Zirkel, John, Kevin Nace, and Chris Ziem. *Aircraft Carrier Reference Data Manual.* Revision D, NAEC-MISC-06900, Lakehurst, New Jersey: Naval Air Warfare Center Aircraft Division, November 1997.

Description of the Jet Blast Deflector (JBD)

The function of the JBD is to deflect the hot, high velocity jet exhaust from airplanes preparing for launch on the catapult away from personnel, aircraft, and equipment on the flight deck. The JBD is a series of six aluminum panels that pivot about the end nearest the catapult. The JBD is hydraulically actuated from a position flush with the flight deck to a 50-degree position when fully raised in the launching position. The MK7 MOD 0 JBD panels behind catapults No. 1 and 2 consist of six panels each 6 ft. by 14 ft. The raised height and width of the JBD is 10 ft. 9 in. by 36 ft. A drawing of a typical JBD is shown in Figure 10.

Description of Flight Test Anemometer System

Wind-over-the-deck (WOD) was measured by a Naval Air Warfare Center - (NAWC) Patuxent River calibrated boom anemometer that provided accurate wind velocity and relative bearing. The ship's anemometer system was not used for the CMEA tests because the ship's system was highly damped (time constant of 6 sec) and not accurate enough for this type of testing (SA FTM-01, 1993). The anemometer used for the tests was a Qualimetrics model number 2106 with four bladed turbine designed to operate from 0 to 120 mph and articulate fully in azimuth through 360 degrees. It consisted of an airfoil type streamlined body designed to fair into the free stream. The anemometer was mounted atop a vertical pole measuring 30 feet attached to the flight deck precisely aligned with the ship's centerline. The boom anemometer was placed near

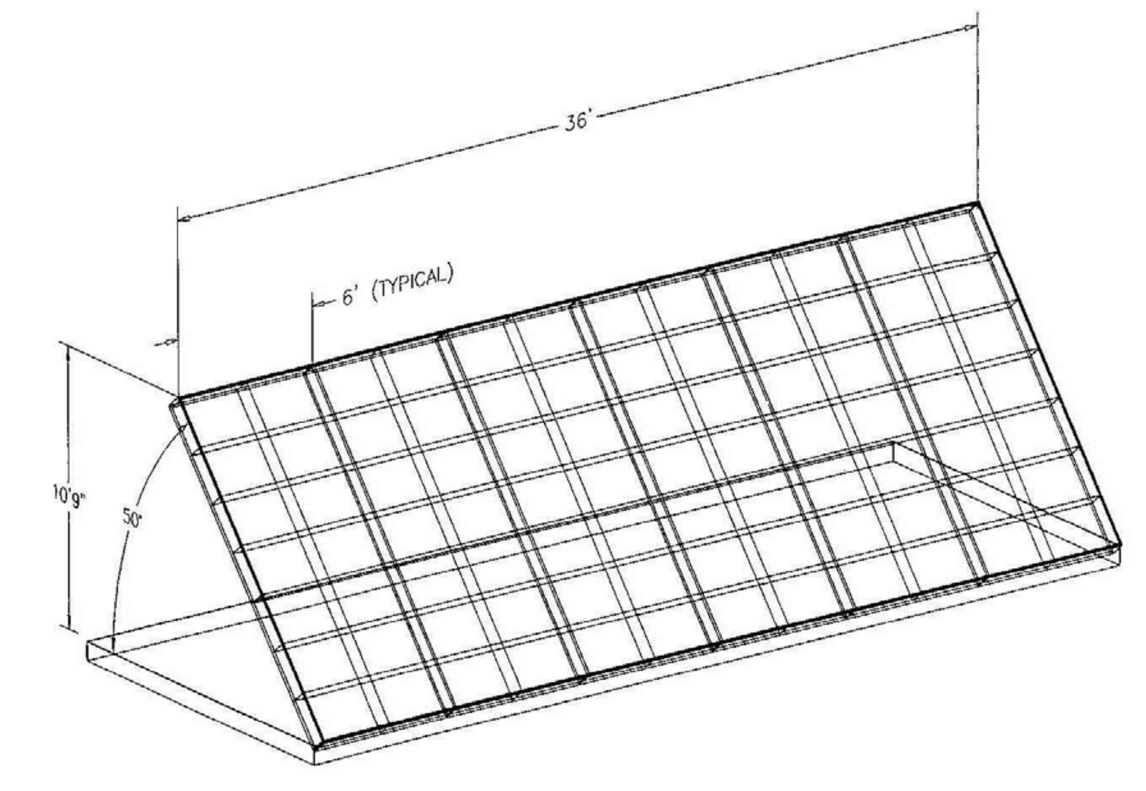


Figure 10. MK 7 MOD 0 Jet Blast Deflector

Source: Zirkel, John, Kevin Nace, and Chris Ziem. *Aircraft Carrier Reference Data Manual.* Revision D, NAEC-MISC-06900, Lakehurst, New Jersey: Naval Air Warfare Center Aircraft Division, November 1997.

the ship’s bow, outboard of catapult No. 2 if using catapult No. 1 and visa versa. The boom anemometer was required for WOD indication during minimum end airspeed determination tests.

Chapter V

Method of Test

Factors Affecting Minimum Airspeed

Six criteria form the lower boundary of the minimum end airspeed. Testing at launch airspeeds below these boundaries is not required or safe. The highest airspeed of the following list defines the catapult minimum airspeed:

a. The power-on aerodynamic stall/absolute minimum airspeed with any high lift devices (flaps, boundary layer control, vectored nozzles, etc.) in the launch configuration. Stall warning airspeed may be used if there is no pilot discernable change between stall warning and stall, or 0.9 $C_{L\ max}$ (SA FTM-01, 1993). The catapult minimum end airspeed is intended to provide at least 4 knots of margin above the absolute minimum speed (Gallagher, et al, 1995).

b. The airspeed where thrust available equals thrust required on the slow side of the curve, also known as the "lockpoint". Even slightly above the lockpoint, an overrotation may be detrimental. Generally, a speed 8 knots above the lockpoint is considered an absolute minimum if launching where the thrust required curve has a steep negative slope (SA FTM-01, 1993). The F/A-18E/F Detailed

Specification (1995) required a level flight longitudinal acceleration ratio (a/g) of 0.065 (1.24 knots/second) with a 90 degree Fahrenheit ambient temperature.

c. Airspeed corresponding to any adverse flying qualities or characteristics due to buffet, wing rock, wing drop, pitch up, and lateral/directional control.

d. The airspeed corresponding to the descent of the center-of-gravity of the airplane after launch of 20 feet from the static plane of the ship's deck. This is also known as the sink-off-the-bow (SOB). The FA-18E/F Detailed Specification modified this criterion to state the CG position of the aircraft shall sink no more than 10 feet from its position at the end of the power stroke.

e. Single engine dynamic minimum control speed (V_{MC}). A multi-engine airplane must be launched at an airspeed that will allow sufficient control authority to counter yawing and rolling forces in the event of an engine failure. Interestingly, positive single engine rate-of-climb is not required for ejection seat equipped aircraft.

f. Response of automatic flight controls. Modern fly-by-wire flight controls, including the F/A-18E/F, automatically attempt to capture the flyaway angle of attack. If any of the primary flight control surface reaches full deflection during the rotation, this defines the minimum end airspeed.

The result is a catapult minimum end airspeed combined from the lower limits set by the highest airspeed of the factors mentioned above. The generalized relationships of the boundaries for the minimum are depicted in Figure 11. Operational launches are typically performed at the minimum end airspeed plus 15 knots as an added measure of safety and to account for variations in catapult performance, pilot technique, and WOD. The CMEA plus 15 knots forms the ALB.

Prerequisites to the Shipboard Test

Prior to the actual shipboard test, as many of the limiting factors as possible were determined or predicted. Stall was well below predicted minimums. Computer simulations of a/g were made and appeared to not be a factor. Buffet above 10.5 deg AOA was a concern but the transient nature was predicted to be acceptable. The sink-off-the-bow predictions were made for all loadings at MIL and MAX thrust and the response of the automatic flight controls was predicted in simulation but was not verified by flight test prior to the shipboard test. The V_{MC} dynamic tests were performed to determine the catapult minimum end airspeed below 58,000 lb GW.

The weight and balance for the test airplane must be determined. Calibrations of the fuel quantity system, air data system, and engine thrust must be made prior to the ship test.

Shorebased Catapults

While shorebased catapults exist, most are built flush with the surrounding runway or have a gradual ramp down from the end of a slightly elevated deck. Shorebased catapults are not capable of performing catapult minimum end airspeed

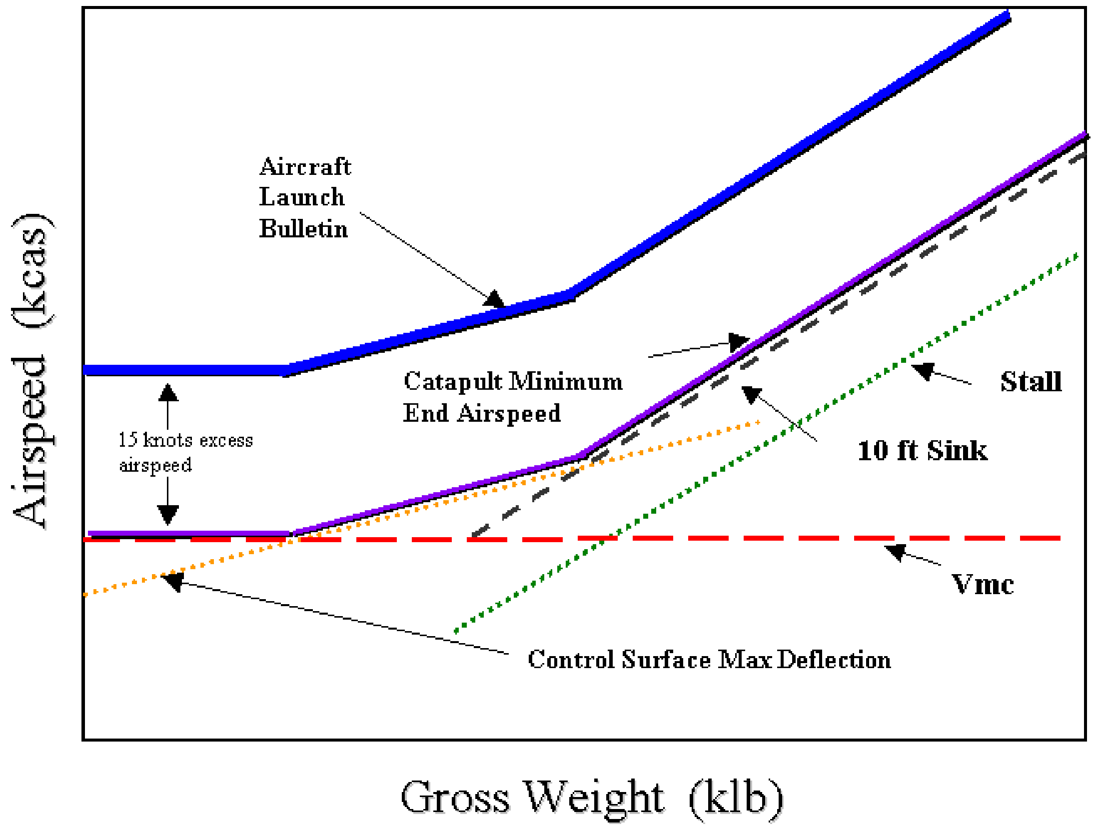


Figure 11. Relationships Between Minimums and the ALB

testing. One difference is the condition at which rotation occurs. At the shorebased catapults, the rotation occurs about the main landing gear while still rolling along the ground.   The airplane also initially flies away in ground effect. Aboard the ship, rotation occurs out of ground effect about the CG after the main landing gear departs the flight deck. A ship can control WOD, whereas a shorebased catapult is at the mercy of nature to provide wind direction and speed.

Shorebased catapults provide an excellent method of training the pilots to utilize the required instruments during the critical flyaway portion of the launch. The pilot can observe how much lag the cockpit airspeed indicator exhibits during the shorebased launches (Bowes and Stento, 1972). The shorebased catapult launches also familiarize the pilots with the flyaway characteristics and any special procedures required for the test. All pilots involved in the test should perform numerous shorebased catapults prior to the shipboard tests. All three F/A-18E/F pilots had numerous opportunities for shorebased catapults during the Ground Loads Demonstration tests and other catapult testing required as a prerequisite to FOST.

Computer Simulation

Computer simulation can be an extremely useful tool for predicting the factors that determine catapult minimum end airspeed. A simple two-degrees of freedom simulation can generally be easily programmed on a small, desktop computer and be particularly useful in predicting sink-off-bow if the aircraft's rotational characteristics are known (Bowes and Stento, 1972). Two degrees of freedom simulation may be adequate for the most basic SOB predictions but has limitations. A much higher fidelity simulation is required for failure mode analysis. Simulation has not proven to be a substitute for flight testing due to unforeseen circumstances or characteristics that can invalidate the simulation. Simulations can suffer from a scarcity of validated airplane characteristic parameter values with approximations of unknown terms (SA FTM-01, 1993).

Extensive computer and flight simulations were performed prior to this shipboard flight test evolution. Several types of simulations were performed in order to determine the predicted airplane performance during the flight test. The simulations were performed at the Boeing Manned Simulator Facility in St. Louis, Missouri using the Modular Six Degree of Freedom (MODSDF) and Manned Flight Hardware Simulator (MFHS), and at the Navy Manned Flight Simulator (MFS) in NAS Patuxent River, Maryland.

The decision to use 10 ft SOB versus 20ft SOB had been determined during computer simulation prior to the first flight of the airplane. The Detailed Specification (1995) set the requirement that

> the minimum end airspeed the aircraft shall sink no more than 10 feet from its position at the end of the power stroke, with a deck run not to exceed 32 feet (distance from the end of the power stroke to round down, without exceeding the angle of attack for 0.9 $C_{L\,max}$ and with cockpit control position fixed.

A reason to use 10 ft SOB instead of 20 ft was due to the prediction that with flaps FULL, the aircraft exhibited an unacceptable trend for excessive additional SOB with only small reductions in end airspeed at the 20 ft SOB minimum. The depiction of the sensitivity to SOB for MIL and MAX power at FULL flaps is shown in Figure 12. At MIL, the sensitivity at 20 ft SOB was 7 ft/knot and at MAX it was 3.5 ft/knot at heavy gross weights. If the actual minimum test launch was 4 knots below planned, the airplane would settle an additional 28 feet. The aircraft carrier's deck height of 60 feet above the water left little margin for reaction time and emergency procedures to take effect.

Boeing developed launch performance models to predict the minimum end airspeed required to achieve 10 ft SOB. The launch performance model simulation was performed on the MODSDF system during automated processing not requiring a pilot. Piloted simulation evaluated test methods, developed emergency procedures, and verified MODSDF results at the Boeing St. Louis and NAS Patuxent River MFS. To ensure the most accurate data in simulation, the simulator aerodynamic database was updated with the most current flight test data prior to beginning any of the simulation related to the testing.

Once a predicted launch model was determined, several degraded launch modes were evaluated in simulation to identify hazardous failure modes and, if required, develop the appropriate emergency procedures. Several areas were investigated to determine the sensitivity of the failure to SOB and whether any unique emergency procedures were

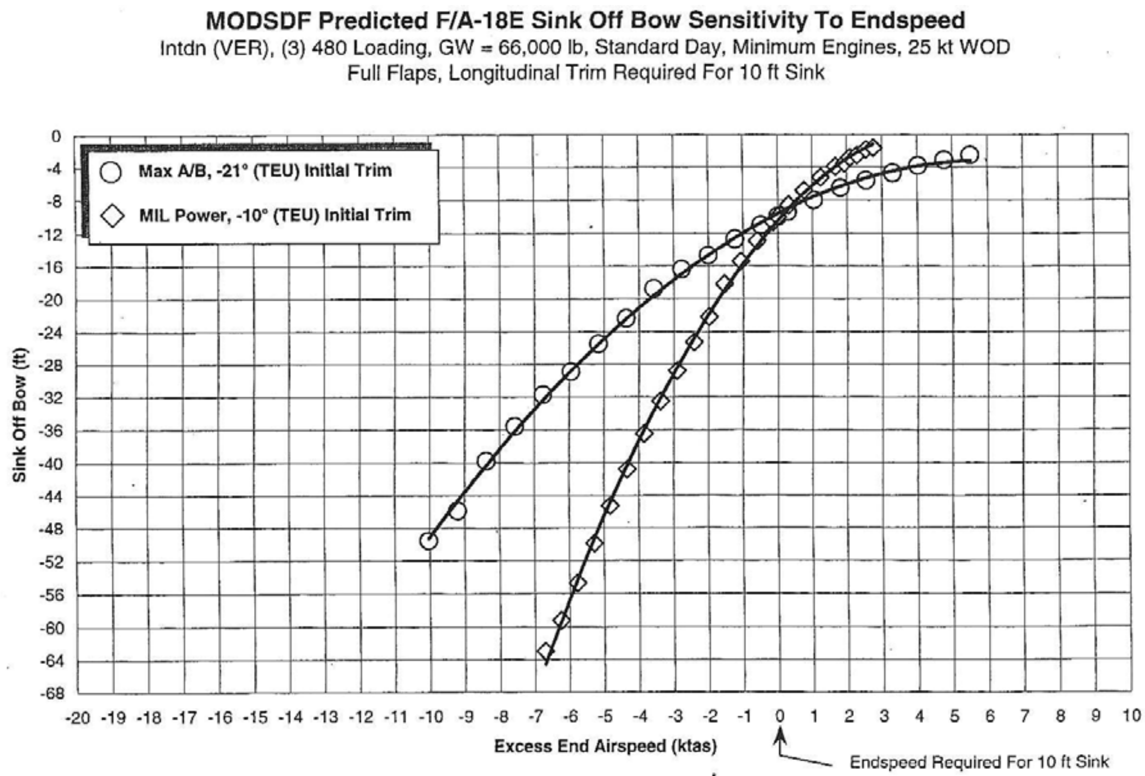


Figure 12. Sensitivity of Airspeed to Sink-off-Bow

Source: *Follow-On Sea Trials.* Test Work Description FMV08.07-004, FA-18E/F Integrated Test Team, NAS Patuxent River, MD, February 1999.

required for the test. The areas of interest were single engine failures, ABLIM remaining engaged, engine pop stall due to exhaust gas reingestion, and engine stall due to steam ingestion.

Boeing used the MODSDF simulator to analyze the sensitivity to SOB due to thrust loss for multiple scenarios that could potentially occur during the test. An example of the data developed is depicted in Figure A-1. Figure A-1 displays a time history of critical parameters for a specific condition and failure mode. The SOB criteria for the failure mode analysis was set to 18 ft SOB to presume a worst-case scenario for a minimum airspeed launch attempt resulting in an end airspeed 3.5 knots below the target. Thousands of MODSDF runs were completed in preparation for the minimum end airspeed tests. This data was highly useful in determining the most hazardous failure modes. The results confirmed the most likely critical failure mode was a single engine failure during a minimum end airspeed launch. The predicted additional SOB was 22 ft if the external stores were retained (Miller, 1999). Other much less likely scenarios resulted in over 60 feet of SOB if the external stores were not jettisoned. The MIL thrust launches had the safety measure of advancing throttles into full afterburner to achieve MAX thrust for additional climb rate. The jettison of the external stores was enough in all loadings to produce a very rapid transition to a positive rate of climb at airspeeds well below the predicted minimum. The Emergency Catapult Flyaway procedure developed by the author and incorporated into the F/A-18E/F NATOPS manual was as follows:

1. Throttles - MAX
2. Rudder - Full against yaw/roll
3. Emergency Jettison button - PUSH
4. Maintain 10-12 degrees pitch with the waterline symbol not to exceed 14 degrees AOA (AOA tone). Do not exceed 1/2 lateral stick.

If uncontrollable or settle not stopped-

5. EJECT

If controllable and settle stopped-

6. Accelerate to onspeed (8.1 degrees) AOA for climb.

Another potential hazard was ABLIM remaining engaged. While the simulation showed that this was critical for the minimum end airspeed test, it would not produce much additional settle for nominal launches. Also, shorebased catapult flight testing prior to the ship tests demonstrated the system operated as designed making the probability for that failure mode highly unlikely.

Surprisingly, none of the engine pop stall scenarios were as critical as initially imagined by some test team members including the author. The flight test data from previous pop stall events due to hot gas reingestion or steam ingestion showed that the stall was self-clearing and the engine recovered rapidly to full thrust. The flight test data was incorporated into the simulation to model previously displayed transient thrust loss and engine stall recovery performance. The MODSDF simulation data predicted a worst case additional settle of 8 ft for a single engine stall and 16 ft for a dual engine stall at the end of the catapult stroke during a minimum launch. Stalls resulting from hot gas reingestion at the beginning of the catapult stroke were predicted to result in only 5 ft additional SOB.

Ground Loads Demonstration with External Stores

Prior to launching or landing aboard an aircraft carrier with external stores, the airplane had to demonstrate structural integrity and robustness with external stores mounted on the under wing pylons. The ground loads demonstration was a continuation of the testing performed in the "clean" configuration, with only wingtip and station 5 and 7 missiles. The ground loads demonstration testing for external stores took place between June 1997 and May 1999. The critical ground loads testing to clear the external stores loadings to be utilized during the FOST was completed in February 1999.
The ground loads demonstration testing consisted of various catapult and arrested landing tests. The catapult tests included N_x up to 5.5 g and off-center alignment of the main landing gear of up to 24 inches. Each critical loading had to complete all demonstration points prior to clearance for shipboard operations. The entire Ground Loads Demonstration effort required 125 flights, 370 shorebased catapults, 471 shorebased arrested landings, and three years to achieve 107 demonstration points. The arrested landing tests conditions are depicted in Table 2.

Table 2. F/A-18E/F Ground Loads Demonstration Test Conditions

Test Point	Sink Rate (ft/sec)	Pitch (deg)	Roll (deg)	Yaw (deg)	Hook Load (lb)	Notes
Mean Pitch Attitude High Sink Rate	≥21.1	3.1 - 6.1	-	-	-	Three points. One with cable rollover near max load.
Nose Down Pitch Attitude High Sink	≥21.1	≤0.1	-	-	-	Three points. One with cable rollover near max load.
Tail Down Pitch Attitude High Sink	≥21.1	≥9.1	-	-	-	
Rolled / Yawed Opposite	≥16.9	-	≥ -5	≥ 5	-	
Rolled / Yawed Same direction	≥16.9	-	≥ 5	≥ 5	-	
Free Flight*	≤ 9.4	≥12.2	-	-	≥ 170,850	Three points. *Cable engagement prior to main tire touch down.
Maximum Hook Load	≥16.9	-	-	-	≥ 201,000	
Maximum Hook Load, Off Center	≥16.9	-	-	-	≥ 201,000	20 feet off center cable engagement.
Rolled	≥16.9	3.6 - 5.6	≥ 6	-	-	

Adapted from *Demonstration Requirements for F/A-18E/F Aircraft*, Combined Addendum 131 and Basic MIL-D-8708B, Washington, D.C.: Department of the Navy, Naval Air Systems Command, February 1992.

Vmc Dynamic

Single engine minimum control speed (V_{MC}) must be determined for multi-engine airplanes. The V_{MC} dynamic airspeed provides adequate directional control in case of a sudden engine failure. The V_{MC} static airspeed is the slowest airspeed the airplane can be flown at a steady heading with an engine failed. The V_{MC} dynamic airspeed will normally be higher than V_{MC} static, and therefore more of a limiting factor to the ALB, than the V_{MC} static airspeed. The technique for achieving the V_{MC} dynamic airspeed is stabilizing at an airspeed and performing a throttle split, waiting a predetermined amount of reaction time and applying recovery controls (Langdon and Cross, 1981). The V_{MC} dynamic airspeed may be different for different airplane configurations and external store loadings. V_{MC} dynamic for each configuration and loading planned as a catapult launch configuration must be determined prior to catapult minimum end airspeed tests. The F/A-18E/F V_{MC} dynamic airspeed was determined to be 135 KEAS for sea level standard day conditions for the most adverse symmetrical external loading with configuration flaps FULL.

ABLIM Functionality

The airplane was tested at NAES Lakehurst, New Jersey after ABLIM software was incorporated into the FADEC. The airplane was placed in front of the JBD at the 58 foot position with ABLIM engaged. With the throttles commanded to the full afterburner position, the FADEC software sent a command to the engines as if the throttles were set to a half afterburner position. No engine pop stalls were noted during the JBD test with ABLIM engaged.

The airplane was then launched from a shorebased catapult to verify the functionality of ABLIM during the launch sequence. Nominal launches were performed as well as degraded launches with the Inertial Navigation System turned off.
Not having inputs from the Inertial Navigation System removed the filtered longitudinal acceleration input to the ABLIM function: the primary latch to cut off ABLIM. This tested the airspeed latch to cut off ABLIM. All launches demonstrated that ABLIM functioned as designed with no anomalies noted.

Jet Blast Deflector Compatibility

Before ABLIM was incorporated, the heat impinging on the JBD from the F414-GE-400 engines was high enough to require a cooling flow modification to the JBD (F/A-18E/F Acoustic/Thermal Environment Survey TWD, 1996). After ABLIM was incorporated, JBD compatibility tests evaluated the reduction of the afterburner plume temperature on the JBD. The JBD modification was not required after ABLIM was incorporated.

Configuration Selection

The airplane high lift device configuration, external store loadings, CG location, and engine power settings must be carefully considered so that the final results are applicable to the wide range of operations expected in service. Normally, maximum lift is desired to achieve the lowest launch airspeed. However, the highest lift configuration of flaps/engine bleed may increase drag and decrease thrust to the point where another configuration is more desirable. The F/A-18E/F launch configuration was a flap setting of FULL. The leading edge flaps were programmed to 15 degrees leading edge down and the trailing edge flaps were programmed to 40 degrees trailing edge down in the FULL flap setting with weight on wheels. Once airborne, the LEFs schedule as a function of AOA.

The external store configuration affects drag, rotational inertia, CG location, and wing-to-tail flow interference. Critical combinations of these factors must be selected for the test as it affects excess thrust, rotation characteristics, and SOB. The external store loadings selected for the F/A-18E/F CMEA tests are depicted in Chapter II, Figure 4. These loadings were selected to achieve the launch GW with a representative drag count and allow for jettison of some of the stores to achieve recovery GW prior to the arrested landing aboard the carrier. There were other possible store loadings that would have resulted in higher drag counts. Those store loadings were not chosen because they offered only a small increment in drag count and were too valuable to allow for jettison prior to carrier recovery.

Engine Preparation

In past CMEA tests, engines used for testing were adjusted to produce the manufacturers guaranteed minimum thrust. This provided the most conservative ALB for the service life of the airplane, allowing for engine deterioration. All tests should be conducted with representative bleed and horsepower extraction systems operating (SA FTM-01, 1993).

The F414-GE-400 engine with the FADEC was designed to produce constant thrust at MIL and MAX over the first 2500 hours of engine operation. Due to the FADEC, no engine adjustments were possible for the test. Bleed air extraction was operated in a normal mode with bleed air extracted from both engines to operate the fuel system pressurization system, environmental control system, and on-board oxygen generating system. Each engine powered all normal accessories including the fuel pump, hydraulic pump, alternating current generator and direct current permanent magnet generator through the Aircraft Mounted Accessory Drive.

Surface Position Calibrations

Surface calibrations were conducted within 6 months prior to shipboard testing.

All aircraft surface positions, except the digital MUX Bus surface deflections, were calibrated using Boeing supplied calibration procedures. The calibrations were performed with control surfaces installed on the aircraft. That ensured the information gathered from the aircraft instrumentation system was a true representation of surface position deflections (FOST TWD, 1999).

Shipboard Procedures

Exclusive deck time was requested to perform the tests. The ship's Captain and appropriate crew were briefed on the operations and special procedures during the Pre-Sail Conference. All required ordnance was ordered and confirmed loaded aboard well in advance of the ship's departure. The minimum end airspeed tests were planned as a series of five launches at each gross weight. The interval between launches required approximately two hours for post launch fuel adjustment, ordnance jettison, shipboard recovery, post-recovery maintenance, and preparation for the subsequent launch.

Pre-Flight Procedures

Preflight inspection of the instrumentation system was accomplished prior to the first flight each day. Normal preflight activities included recorder checks, telemetry checks, CAIS Built-in Test and parameter listings, along with a real time display verification of selected parameters. The listings were taken after the aircraft was set up to standard conditions (AOA=0 and control surfaces in rig mode) to ensure parameter preflight references were consistent from day to day. The listings and any discrepancies were made available for review by test team members prior to flight. A historical database was maintained of the preflight data values obtained from the preflight listings (FOST TWD, 1999).

Hangar Initialization Record

A hangar initialization record was recorded to the onboard instrumentation data tape during preflight procedures prior to the first flight of the day. The aircraft instrumentation was time synchronized prior to the initialization record. A two minute record was performed in the hangar bay with the external electrical power on, engines off, no airflow in the Environmental Control System (ECS) system, or the engine bleed ducts, and with avionics cooling air supplied to the airplane. This information was used for instrumentation initialization and validation during data processing for each flight (FOST TWD, 1999).

Preflight and Post flight Ambient Records

The test pilot initiated a thirty second preflight and post flight ambient record. These were performed with the aircraft stationary on the flight deck and engines running, with all normal systems operational. This information was used a as reference during data processing.

Conditions Required for the Test

The normal conditions for obtaining catapult minimum end airspeeds are:

- Steady deck (≤ ± 3 feet)
- Steady wind (±2 knots within ±5 degrees from dead ahead)
- Unhurried Operations
- Skilled pilots
- Engines delivering full takeoff thrust
- No turns attempted immediately after launch
- Pilots trained in optimum technique
- Gross weight and CG accurately known
- Accurate WOD measurements
- Corrections for test day conditions incorporated in the launch settings
- Catapult performance accurately known

A steady deck is generally defined as no more than ±3 feet of vertical motion of the flight deck due to sea state. Steady wind is a necessity because it directly influences the accuracy and safety of the test launches. The test cannot be performed within the desired margin of safety if the wind velocity is varying more than 4 knots within a five minute period. The first launch in the minimum series should be conducted at 15 knots above the predicted minimum end airspeed on a bow catapult with wind from dead ahead. After the first launch, the catapult setting is reduced in approximately 3-4 knot increments until the targeted end airspeed is within 10 knots above the predicted minimum. Further reductions in end airspeed must be achieved by reducing the WOD. The build down in WOD is achieved by reducing the ship's speed in 3 to 4 knot increments and maintaining a constant catapult CSV setting until the minimum is attainted. The initial ship speed recommended is 20 knots to allow for adequate reduction to the predicted minimum end airspeed and 6-9 knots below, if required, and still provide adequate speed for ship's steerage (SA FTM-01, 1993). The weather needs to be monitored often. Density correction must be computed at least every 30 minutes and prior to each launch. After the minimums for the bow catapults are determined, the testing continues on the waist catapult to verify the minimum plus 15 knot launches. Since the flow field forward of the waist catapults can be disturbed by the ship's structure or aircraft parked on the bow, the minimum end airspeed tests are not performed on the waist catapults but the operational launches are checked to verify the minimum plus 15 knot launches from the waist catapults are acceptable. Following the waist catapult verification at CMEA plus 15 knots, launches are conducted with crosswinds, and finally with asymmetric stores to complete the Aircraft Launch Bulletin.

Hazard Analysis

A detailed hazard analysis was performed to minimize potential risk during the test. The main concern during CMEA testing was excessive settle off the bow. The causes included insufficient end airspeed and loss of thrust due to pop stalls. The preventative measures for insufficient end airspeed were monitoring longitudinal trim settings, using a methodical build down in excess end airspeed, and monitoring the catapult performance to identify any unusual variations from predicted performance. The preventative measures for pop stalls included the 60 second run up time, compressor variable geometry “kicker” to increase stall margin, ABLIM to reduce hot gas reingestion, improved W-seals, reduced damper clearance number 3 bearings, and MODSDF failure mode simulation to quantify the severity of pop stalls on the SOB (FOST TWD, 1999).

Test Techniques

All launches took place during daylight hours. The pilot’s qualitative comments are a key part of the minimum end airspeed test. The same pilot was highly desired for each minimum launch sequence. A launch sequence of five planned launches would take an entire day to accomplish. This exceeded the Naval Strike Aircraft Test Squadron’s Standard Operating Procedures of three flights per day, but since the flights were short in duration and the same pilot was highly desired during the sequence, the number of flights per day was listed and agreed on in the FOST TWD (1999). Some sequences would have to be halted midway due to weather or mechanical problems and resumed on another day. The same pilot for each sequence was invaluable due to the critical build down in excess end airspeed. The target excess end airspeeds were 15 knots, 10 knots, 6 knots, 3 knots, and finally 0 knots. The build down in target excess end airspeed between 15 knots and 6 knots excess was achieved by catapult end speed reductions with constant WOD. The catapult CSV setting was reduced accordingly to reduce the excess end airspeed down to the 6 knot excess point. The 3 knot and 0 knot excess target points were achieved by holding the CSV setting, and therefore catapult end speed, constant at the 6 knot setting and reducing WOD by reducing ship's speed.

The test team adjusted target excess end airspeeds based on how the actual launches were comparing to the predictions. For example, if the target was 10 knots excess but due to catapult variance and a sudden decrease in wind, the actual end airspeed was 6 knots, as long as the SOB followed a predictable trend, the next target could be 4 knots excess.

The team briefed the pilot on the takeoff longitudinal trim for the predicted test condition to target 10 to 12 deg/sec pitch rate and peak AOA not to exceed 15 degrees. The team briefed special precautions prior to each launch. These included predicted minimum flyaway speed in MAX thrust with external stores jettisoned, singe engine rate-of-climb with stores at MAX thrust, and review of emergency catapult flyaway procedures. The predicted minimum flyaway airspeed was 105 KCAS for loadings C, D, and E with full internal fuel and all external stores jettisoned. The singe engine rate-of-climb ranged from 400 to -400 fpm depending on the initial GW, temperature and excess end airspeed highlighting that a single engine failure required jettison of external stores to stop the settle and climb away.

In order to control the gross weight within the tolerances of ±500 lb required for the test, the airplane had to be refueled to a fuel state approximately 1,500 lb above the test gross weight. After start, the pilot received confirmation of the trim setting from the test conductor for the predicted excess end airspeed, gross weight, and CG. The aircraft was taxied to the catapult and refueled if required to achieve approximately 600 to 1000 lb above the desired GW to allow for a 60 second run up time at MIL or MAX prior to launch. Accommodations were made to enable refueling with the aircraft engines operating while stationed near the launch position on the catapult. This enhanced test efficiency when launches were suspended leaving the airplane below the desired gross weight for the test point.

A normal catapult launch requires approximately 15 seconds at MIL or MAX power to complete airplane checks and catapult safety procedures prior to launch. An engine warm-up of 60 seconds at MIL thrust was required prior to each minimum end airspeed catapult launch to prevent the remote possibility of engine pop stalls due to cool rotor transients. The 60 second period was chosen because it provided adequate engine rotor warm-up time and allowed 30 seconds for the launch before the compressor variable geometry (CVG) "kicker" timed out at 90 seconds.

The test procedure was abnormal for the carrier catapult crew. Therefore, prior to the test, the team briefed the crew on the procedure extensively to ensure everyone involved was aware of the additional engine high power warm-up time. The airplane was connected to the catapult utilizing normal procedures. The catapult crew signaled the pilot when the catapult was ready. The pilot began the launch sequence by increasing the throttles to MIL. The test conductor called out “50 seconds” at which time the pilot completed final aircraft checks, advanced the throttles to MAX if required, and passed a salute to the catapult officer indicating readiness to launch. By the time all the checks where complete and the catapult was fired, over 10 seconds had elapsed to satisfy the 60 second criteria. If for some reason, the launch was delayed beyond 85 seconds, the test conductor would suspend the launch to prevent the CVG “kicker” logic from timing out prior to launch. Suspended launches occurred on several occasions during the tests due to out of limit winds and catapult suspends.

During simulator testing, the author observed the HUD velocity vector was limited at higher AOA during rotation. The velocity vector in the HUD was limited when AOA was greater than 12 degrees. AOA routinely exceeded 12 degrees during the minimum end airspeed launches. The solution was to display the RADAR Attack (RDR ATK) display on the Up-Front Control Display (UFCD) directly in front of the pilot. That display provided a stabilized horizon line and usable velocity vector in a convenient location regardless of AOA. The velocity vector was critical for the pilot to determine flight path trend during the CMEA tests. Use of the RDR ATK display for velocity vector information greatly enhanced the pilot's situational awareness. Figure 13 shows the F/A-18E/F cockpit layout with the RDR ATK display on the UFCD located directly below the HUD.

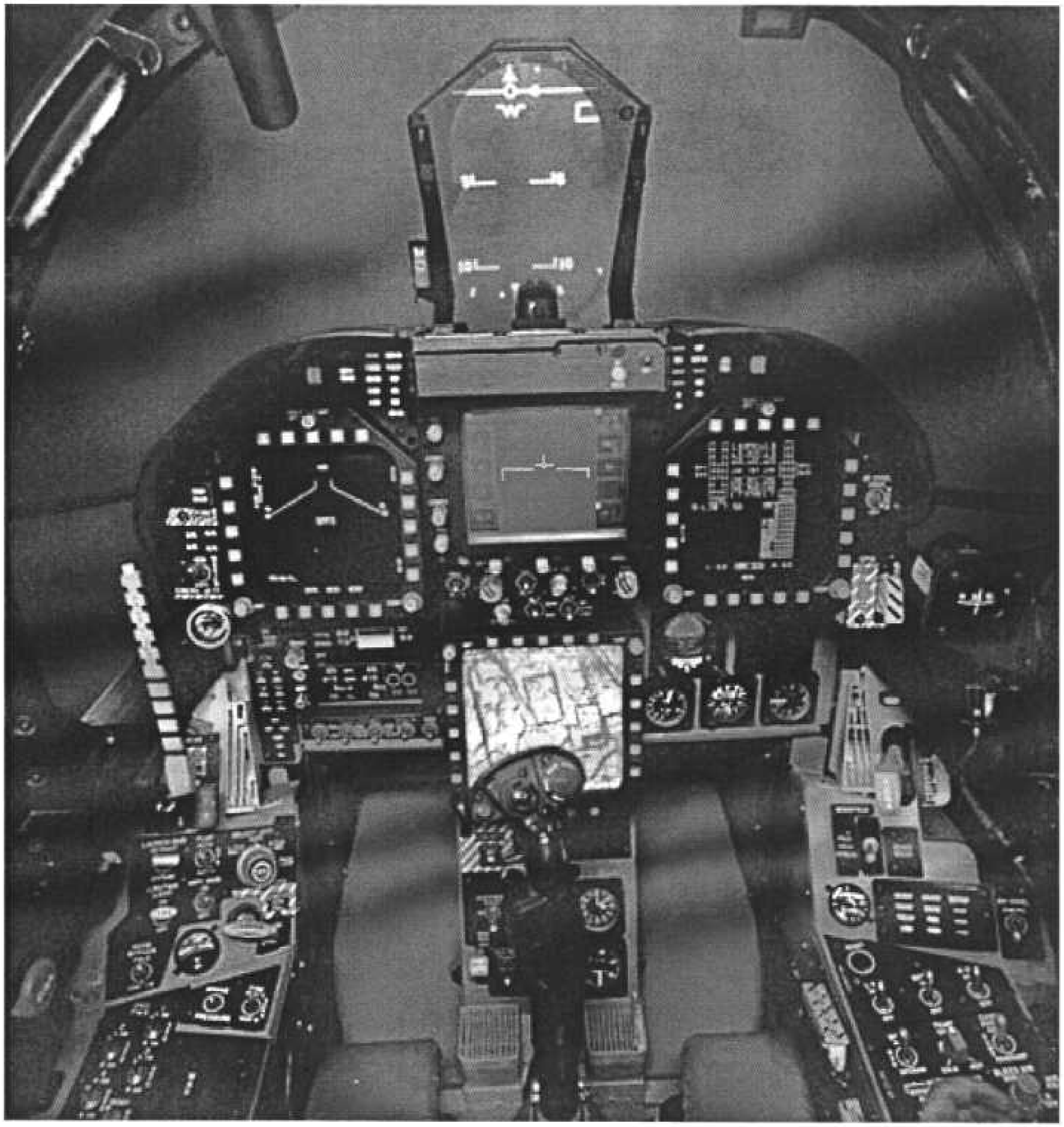


Figure 13. F/A-18E/F Cockpit Layout with RDR ATK Display on UFCD
Source: Boeing Photo modified by the author

Chapter VI

Test Results

Test Point Description and Results

The determination of the catapult minimum end airspeed for the F/A-18E/F consisted of 17 launches in order to define the launch envelope from 58,000 to 66,000 lb. The tests were broken down into two gross weights at MIL and two gross weights at MAX. The relationship between end airspeed and gross weight at a given thrust setting is linear, therefore the two points at each thrust setting determined a line defining the minimum for all gross weights within the range. The sequence of launches used a build-up approach in thrust setting and gross weight. The 58,000 and 63,000 lb gross weights at MIL thrust were tested first because these were determined to be the lowest risk test points due to the availability of afterburner thrust in the event of excessive SOB. The second sets of gross weights tested were 66,000 lb and 61,000 lb MAX thrust points. Previous testing had determined the minimum end airspeed for gross weights below 58,000 lb was limited by V_{MC} speed of 135 KEAS.

The data for each launch was reviewed before a subsequent launch was attempted to determine the trend. The flight test results were adjusted for test day conditions and compared to computer predictions prior to briefing the subsequent test point. The data was corrected for test day conditions and reviewed post flight to determine if an actual SOB of less than 10 ft would be utilized to determine the minimum. In the MIL thrust launches, the acceleration (a/g <0.065) became a factor prior to reaching 10 ft SOB. Ten feet SOB was required to verify the 66,000 lb launch for specification compliance. The results of the launches are presented in Table 3. The time histories of the minimums are contained in Figures A-2, A-3, A-4, and A-5.

F1 roll-off

A slow left roll off was noticed in loadings C, D, and E in aircraft F1 during the minimum launches. The roll rate was generally less than 5 deg/sec and was attributed to an undetermined aerodynamic effect from the external fuel tank loading on that airplane. The pilot procedure for the launches called for no stick input until a positive rate of climb was established in order to allow the flight controls automatic AOA capture feature to rotate the airplane. Allowing the roll off to continue would affect flyaway performance due to decreased lift and was not acceptable during the launch. The author used about 1/4 right rudder pedal to arrest the roll rate and keep the wings level during the initial 63,000 lb launches and the test team agreed this technique was acceptable and would not affect the results. F2 did not exhibit the roll-off.

Table 3. Catapult Minimum End Airspeed Test Results

Date	Side No.	GW (klb)	Thrust	Target Excess (kcas)	Actual Excess (kcas)	Actual Airspeed (kcas)	CG Sink Off Bow (ft)
3/5/99	F1	63.4	MIL	+15	+13.3	158.0	0
3/5/99	F1	62.9	MIL	+9	+7.4	152.0	2.0
3/5/99	**F1**	**63.0**	**MIL**	**+3**	**+2.9**	**149.6**	**4.0**
3/5/99	F2	58.5	MIL	+15	+16.2	149.6	0
3/5/99	F2	58.0	MIL	+10	+8.2	144.1	3.0
3/5/99	**F2**	**58.1**	**MIL**	**+6**	**+1.7**	**136.2**	**6.0**
3/5/99	F2	58.0	MIL	+1	-2.3	132.7	22.0
3/9/99	F1	65.9	MAX	+15	+14	155.8	2.0
3/9/99	F1	65.8	MAX	+11	+12.9	154.7	4.0
3/9/99	F1	65.9	MAX	+10	+11.6	153.0	3.0
3/9/99	F2	60.7	MAX	+15	+14.4	146.0	2.5
3/9/99	F2	60.7	MAX	+11	+14.1	145.9	1.5
3/11/99	F1	66.1	MAX	+9	+4.7	146.6	8.0
3/11/99	**F1**	**65.9**	**MAX**	**0**	**+0.8**	**145.7**	**10.0**
3/11/99	F1	60.7	MAX	+6	+8.4	144.3	4.0
3/11/99	F1	60.9	MAX	+4	+3.4	139.4	7.5
3/11/99	**F1**	**60.8**	**MAX**	**0**	**+0.4**	**137.3**	**7.0**

Note: Bold type indicates the test point used to determine the Catapult Minimum End Airspeed for the given gross weight.

Source: Niewald, P. W., G. M. Cvengros, K. J. Zonies, David M. Anderson, Bret A. Marks. *Demonstration Data Report for the F/A-18E/F Aircraft*. Report number MDA 95A0046 Revision D. St. Louis, Missouri: 1999.

Launch Events

The launches were separated into the following order. The 63,000 lb MIL sequence consisted of three launches conducted on March 5, 1999. The 58,000 lb MIL sequence consisted of four test points conducted on March 5, 1999 in F2. Three launches at 66,000 lb and two launches at 61,000 lb were conducted on March 9, 1999 in F1 and F2 respectively. Two launches at 66,000 lb and three launches at 61,000 lb were conducted on March 11, 1999 in F1.

There was a delay initiating the first launch on March 5 due to the position of the ship. The test team passed a desired launch location latitude and longitude the prior day to the Navigation Department that would place the ship approximately 100 NM from the nearest divert. A fuel reserve for at least two approaches to the carrier deck was desirable during operations aboard the aircraft carrier in the event the arresting hook did not engage any of the four cables, known as cross deck pendants, during landing and still have fuel remaining for a divert to land ashore if required. A 100 NM divert airfield range was the maximum acceptable with the recovery loadings to allow for two approaches. During the morning pre-flight briefing, the author noticed the location of the ship was over 200 NM from the nearest divert location. The latitude was correct but the longitude was 2 degrees east of the desired position. The 200 NM divert range from the ship prevented operations because the planned recovery loading (Loading J) resulted in a recovery fuel load below that required for a divert. A call was placed to the bridge identifying the issue and within minutes the ship transitioned from a calm troll of a few knots for steerage, turned due west and proceeded at an impressive maximum speed for a 95,000 ton ship toward the desired launch position. As it would turn out, the Navigation Department had misinterpreted the desired position, and maneuvered the ship directly and precisely to a point two degrees farther east in longitude than desired.

The location error delayed operations for three hours. The ship was able to close to approximately 120 NM from the divert airfield. That resulted in allowing only enough fuel for one approach due to the recovery loading. If the cable was missed or the aircraft was waved off on the first approach, the aircraft would have to divert to land ashore. The test team agreed this was acceptable and began testing in order not to lose the entire day. The boarding rate on March 5, 1999 was 100 percent and therefore no diverts were required. On subsequent test days, instead of passing a desired launch location, the test team only specified the maximum divert range allowable to prevent any confusion.

58,000 MIL Launches

The 58,000 lb MIL launch sequence was executed in F2 on March 5, 1999 while F1 launched at 63,000 lb. The wind had begun to gust during the first couple of launches. The gusts were intermittent and varied in magnitude up to about 5 knots. The test team decided there were sufficient periods of steady wind to continue the testing. The build-down had proceeded normally with target excess end airspeeds of 15, 10, and 6 knots resulting in 0, 3, 6 feet SOB respectively for the first three launches. On the fourth launch, the target was 1 knot excess end airspeed, a 5 knot decrease from the previous point, which was predicted to achieve 8 feet SOB. The catapult end speed was 0.3 knots below the predicted trend and a wind gust decreased the anticipated headwind by 2 knots. The result was an airspeed 2.3 knots below the predicted minimum. The pilot noted the additional settle and initiated afterburner to arrest it as the AOA tone at 14 deg AOA became steady. The pilot noted an immediate acceleration and arrestment of the settle (F2 Flight Report, 1999). The resulting SOB was 22 feet. The predicted SOB for the actual end airspeed was 26 feet if the pilot had remained in MIL. This launch highlighted the significance of the sensitivity of SOB to end airspeed. It also served to demonstrate the margin of safety designed into the test through the hazard analysis. Engaging afterburner was the first step to arrest an excessive settle for the MIL thrust test points. If the settle was not arrested in MAX thrust, the next step was the jettison of external stores which would reduce the gross weight significantly and result in flyaway at airspeeds as low 105 KCAS.

63,000 MIL Launches

The 63,000 MIL thrust launches proceeded normally with steady build down in excess end airspeed. The longitudinal acceleration of the aircraft for each launch was steadily decreasing with each decrease in excess end airspeed. On the third launch, the sink-off-bow was only 4 ft but low longitudinal acceleration was noted during the rotation. The a/g was below the 0.065 threshold and therefore defined the minimum for this gross weight.

61,000 MAX Launches

After two launches, the winds became too gusty and were suspended. Two days later the sequence was resumed and the minimum of 7 feet of SOB was accepted after two more launches. Although 10 ft SOB was not achieved, this gross weight was not required for specification compliance but to form the lower point of the MAX launch minimum line. Due to the difficulty in achieving an increase in SOB during the last two test points and the building schedule constraints, the team decided to accept 7 ft SOB as a final test point at 61,000 lb.

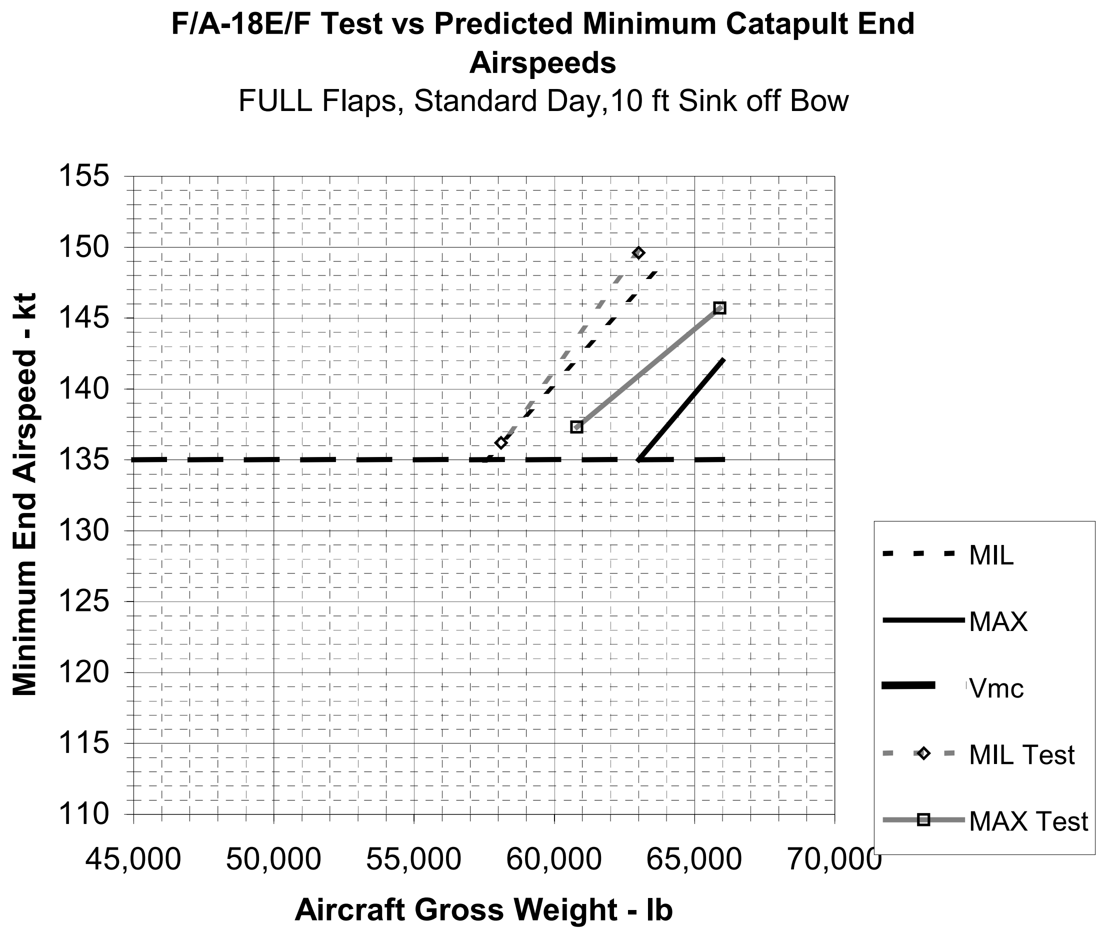
66,000 MAX Launches

Gusty winds caused a break in this launch sequence after three build down launches. Testing was continued two days later and the last two launches were performed. The fourth launch resulted in 8 ft of SOB. The longitudinal acceleration was noticeably higher than the 63,000 lb MIL launches (F1 Flight Report, 1999). Due to schedule restraints and the desire to not repeat an event like the 58,000 lb launch, there was significant debate by the team about the value added by launching again to achieve 10 ft. SOB. There were several members of the test team who thought the SOB trend had been established, could be compared to predictions to determine the minimum and there was no need to continue any farther. A slim margin for specification compliance appeared to exist but without post flight analysis, no one could be sure. The only way to be sure was to go to 10 ft SOB. After several lengthy debates on the issue, the decision was made to proceed with the launch to achieve 10 ft SOB. The final launch achieved the target 10 ft SOB uneventfully. The non-normalized results are plotted with the predicted minimums in Figure 14.

Issues

Light buffet was noted during nominal launches above 10.5 deg AOA at heavy gross weights during rotation. This was deemed a minor deficiency, more of an annoyance to the pilot, because the airplane was performing as designed during the catapult launch and the duration of the buffet was limited to a few seconds as the airplane accelerated.

The longitudinal trim schedule was noted to be somewhat cumbersome as it was affected directly by aircraft CG, which could change up to one percent as fuel was burned on deck awaiting takeoff.



Note: Flight test data not corrected for test day conditions

Figure 14. Flight Test Comparison to Predictions

Chapter VII

Conclusions

Specification Compliance

During post flight analysis, the flight test data was reviewed and corrected from test day conditions to tropic day conditions for specification compliance purposes. The WOD requirement was computed using known C7 catapult performance.

The F/A-18E/F met the specification requirement of less than 30 knots of of WOD at maximum gross weight of 66,000 lb. for C7 catapult (no longer in use on any operational carrier) with a 2 knot margin. The WOD for C13-1 catapult launch at maximum gross weight was 19 knots. The MAX power launch bulletin was derived based on demonstrated catapult minimum end airspeeds due to sink-off-the-bow. The MIL thrust launch bulletin was developed based on test day launch data based on the acceleration limited 0.065 static a/g condition (Niewald, et al, 1999).

Flying Qualities

The Super Hornet exhibited acceptable flying qualities during all launches. The aircraft responded as predicted during the minimum catapult end airspeed launches as the rotation occurred after launch and the airplane automatically rotated to capture 12 degrees AOA. Momentary excursions as high as 14.6 AOA were predicted and encountered on a few launches. Light buffet was experienced when AOA went above 10.5 degrees AOA during the rotation. The buffet initially received attention as a possible annoying characteristic. Light buffet was only encountered during the heavier gross weight launches with less than 15 knots of excess end airspeed, therefore was not deemed to be a concern since the normal launch bulletin was based on 15 knots excess launches. The pitch rates were also comfortable and never exceeded 12 degrees per second. The slow left roll exhibited by F1 was attributed to the tank loading on that airplane. F2 did not exhibit any roll during the CMEA tests it performed.

Suitability

Based on the results of the flight tests, the Aircraft Launch Bulletin was generated. OPEVAL catapult launches were not restricted from the desired envelope up to maximum gross weight. F/A-18E/F was deemed suitable for launch from all operational U. S. Navy aircraft carriers. The first deployment of the F/A-18E occurred in July 2002 with Strike Fighter Squadron One One Five (VFA-115).

Summary

The measurement of catapult minimum end speed requires an extensive effort in preparation and execution. Liaison with the aircraft carrier prior to and during the test evolution was essential for smooth execution of these critical tests. The Pre-Sail

Conference was a key factor in explaining how the tests would be done and clarifying any questions from the ship's personnel.

The factors that affect the minimum airspeed are the power-on aerodynamic stall airspeed, the "lockpoint", adverse flying qualities or characteristics, sink-off-the-bow criteria, single engine minimum control speed (V_{MC}), and response of automatic flight controls. Generally, the minimum end airspeed is a combination of several of the factors. In the case of F/A-18E/F, the ALB was based on V_{MC} below 58,000 lb, a/g for MIL launches from 58,000 to 63,000 lb, and SOB for MAX launches above 60,000 lb. Shorebased catapults do not provide the same environment a shipbased catapults. Computer simulation is a valuable tool for predicting minimum end speed factors, but is not a replacement. The simulator provides excellent procedure practice for the pilots. The simulation utilized for the F/A-18E/F catapult minimum end airspeed test proved to be invaluable in identifying the most critical failure modes. The simulation also provided the pilots an excellent opportunity to develop and practice routine and emergency procedures prior to the flight test.

The final test must be conducted aboard the ship in a well-controlled environment. The catapult minimum end airspeed is determined by a careful build-down approach. Excessive decrements in excess end airspeed can result in less predictability and safety margin. With proper hazard analysis and emergency procedures, the test can be conducted with an acceptable margin of safety. Achieving the minimum end airspeed provides an Aircraft Launch Bulletin that gives the operational fleet maximum utility from the airplane.

There is a limited amount of current published work on performing CMEA testing and much of it is outdated. The F/A-18E/F CMEA tests were an outstanding example of how the tests can be carried out in a safe manner.

The decision to use 10 feet SOB instead of 20 was determined very early in the program and proved appropriate during the 58,000 lb launch when a wind gust reduced the wind by 2 knots at the end of the catapult with a target excess of only 1 knot. The resulting end airspeed was 2.3 knots below the predicted minimum. The pilot detected the excessive settle and staged afterburner as the airplane settled a total of 22 feet before climbing.

Recommendations

Based on the experiences from this test, the following recommendations are submitted for future catapult minimum end airspeed tests.

1. Review flight test manuals, Detail Specification, former test reports, and any other literature available regarding the test.

2. Utilize the simulator extensively for failure mode prediction and pilot training, and emergency procedure practice.

3. Conduct thorough shorebased catapult build-up with all pilots.

4. Brief the ship's Captain and appropriate crew on special procedures as early as possible.

5. Understand the limiting factors for the specific minimum.

6. Develop a thorough hazard analysis to mitigate the risk as much as possible.

7. Use the RDR ATK display on the UFCD (or similar display for other aircraft) for velocity vector reference.

8. Do not decrement target launch excess end airspeed by more than 4 knots when below 10 knots excess end airspeed.

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APPENDIX

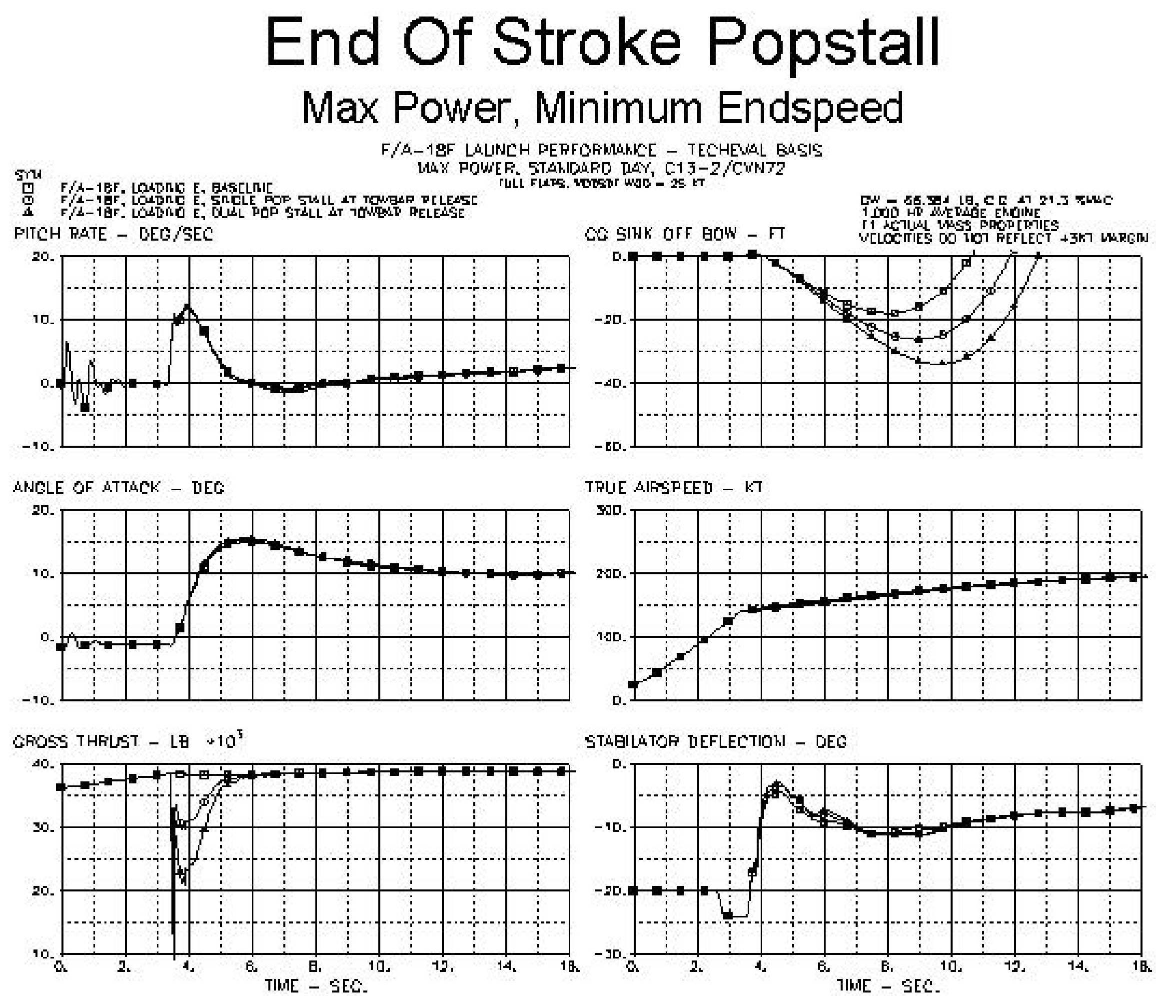

Figure A-1. MODSDF Simulator Failure Analysis Time History

Source: Miller, Gregory. *F/A-18E/F High Lift Configuration Performance, Pop Stall Summary.* St. Louis, Missouri: Briefing presented January 1999.

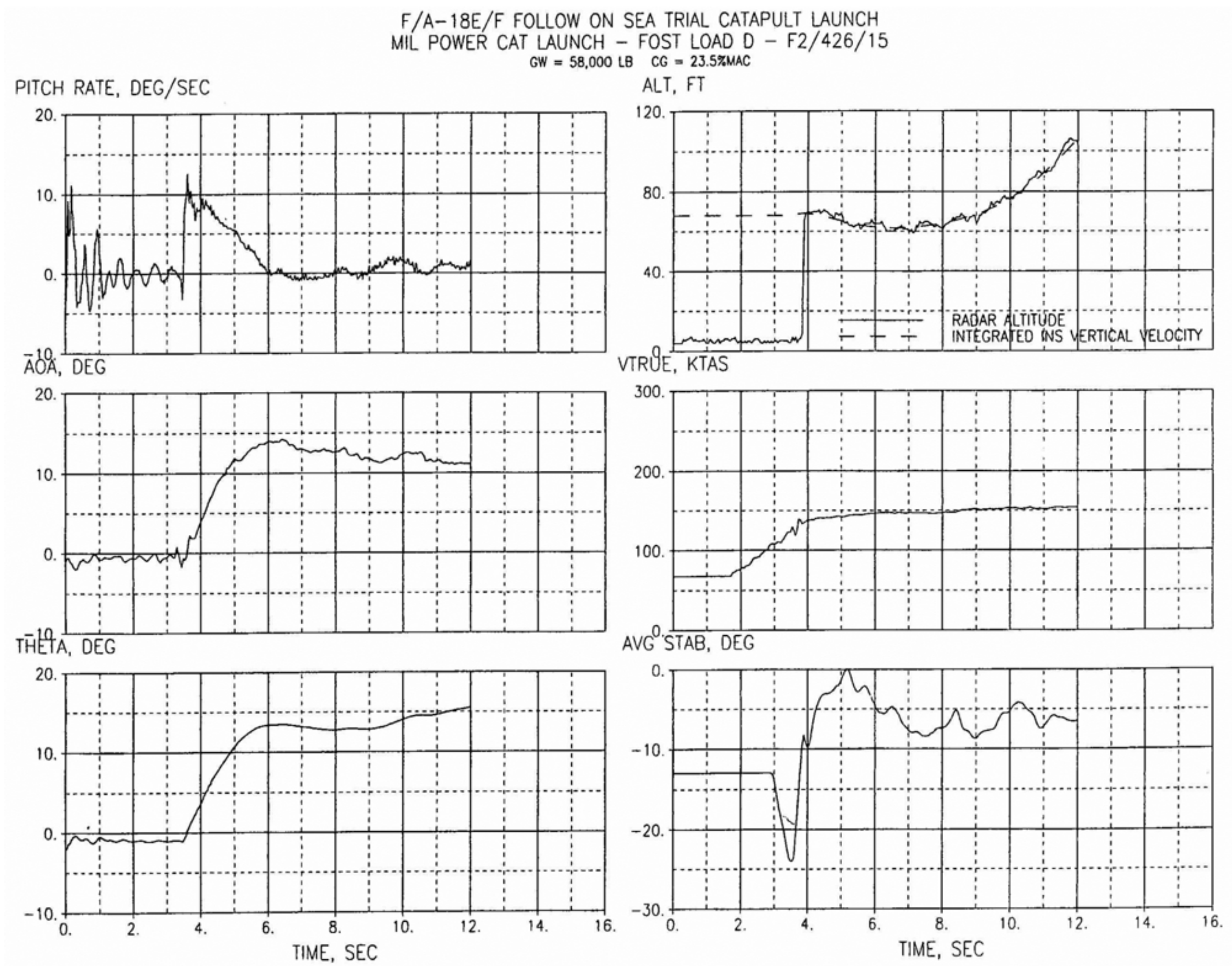

Figure A-2. 58,000 lb Time History

Source: Niewald, et al. *Demonstration Data Report for the F/A-18E/F Aircraft*. Report number MDA 95A0046 Revision D. St. Louis, Missouri: 1999.

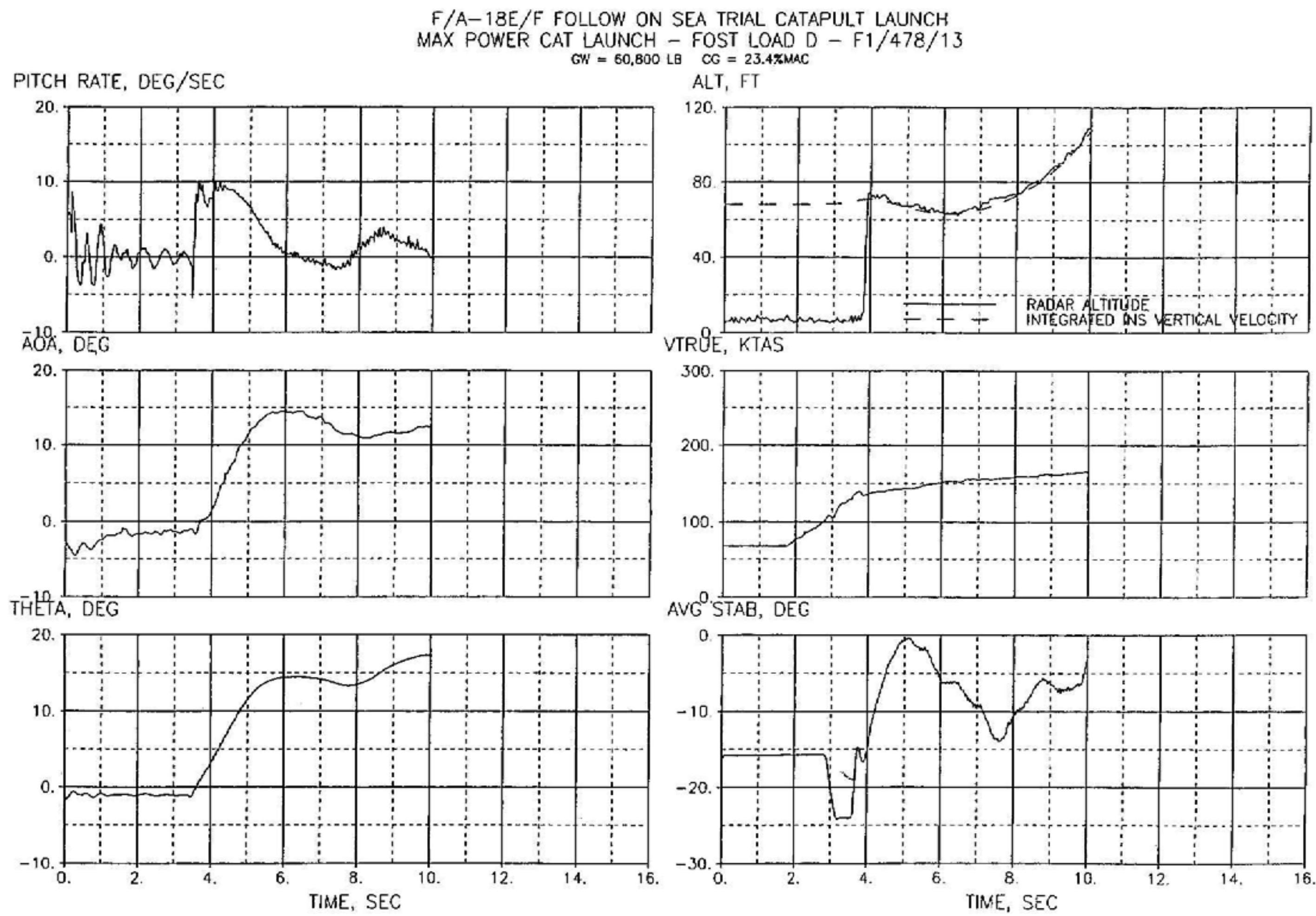

Figure A-3. 61,000 lb Time History

Source: Niewald, et al. *Demonstration Data Report for the F/A-18E/F Aircraft*. Report number MDA 95A0046 Revision D. St. Louis, Missouri: 1999.

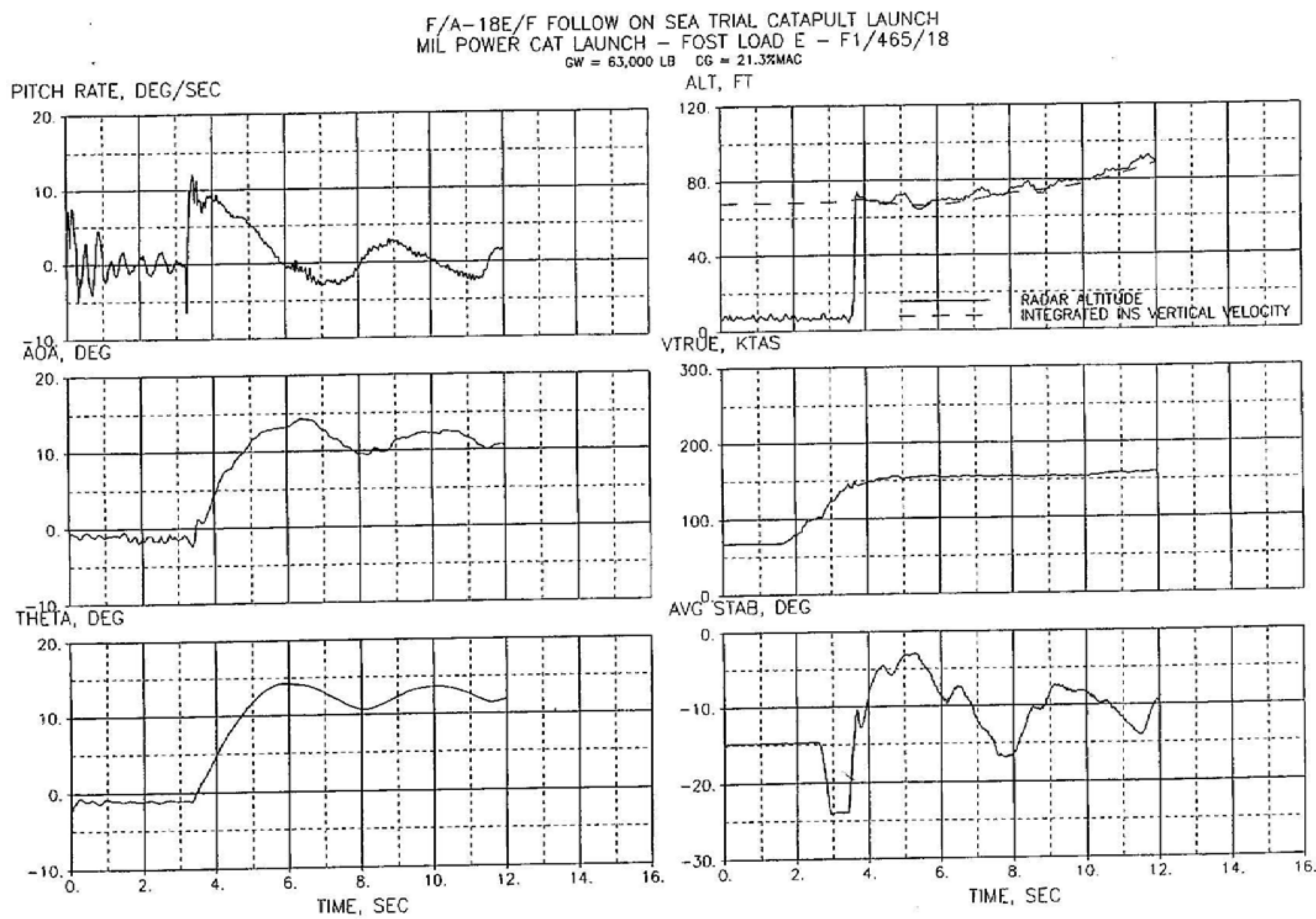

Figure A-4. 63,000 lb Time History

Source: Niewald, et al. *Demonstration Data Report for the F/A-18E/F Aircraft*. Report number MDA 95A0046 Revision D. St. Louis, Missouri: 1999.

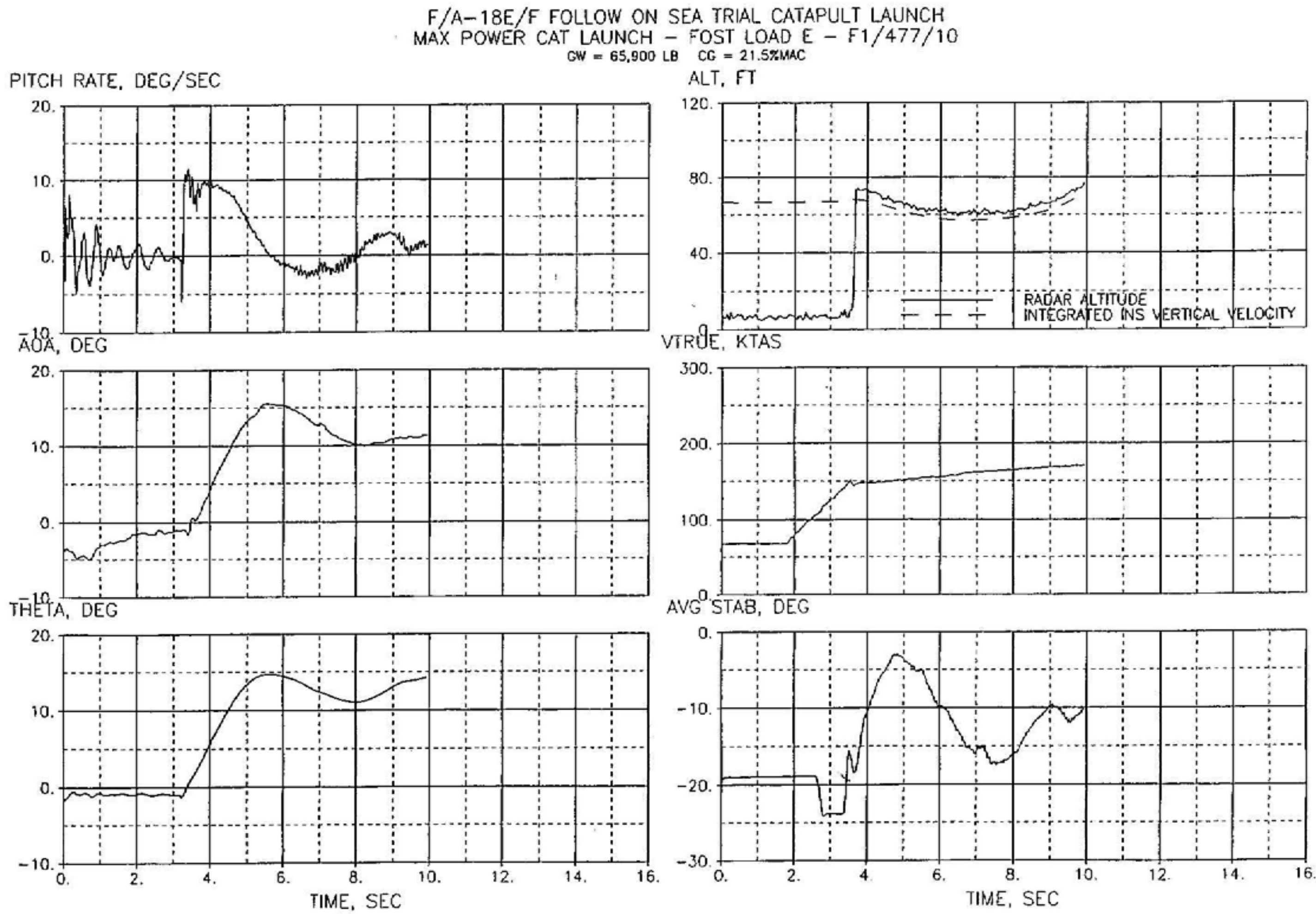

Figure A-5. 66,000 lb Time History

Source: Niewald, et al. *Demonstration Data Report for the F/A-18E/F Aircraft*. Report number MDA 95A0046 Revision D. St. Louis, Missouri: 1999.

Vita

Michael M. Wallace was born on November 1, 1964 in Chandler, Arizona. He graduated from Valley High School in Las Vegas, Nevada in 1982. He graduated from the University of Nevada-Reno in 1987 with a Bachelor of Science Degree in Mechanical Engineering. He attended Aviation Officer Candidate School in Pensacola, Florida and was commissioned an Officer in the United States Navy in December 1987.

Upon completion of jet flight training in November 1988 in Beeville, Texas, Mr. Wallace was assigned as a flight instructor at VT-26 in Beeville. He was selected for F/A-18 Hornet training in 1992 at Lemoore, CA in VFA-125. Serving in VFA-94, he deployed twice aboard USS ABRAHAM LINCOLN in 1993 and 1995 to the Persian Gulf in support of Operations SOUTHERN WATCH and CONTINUE HOPE in Somalia. He graduated from U. S. Naval Test Pilot School Class 110 in 1996. He served at Naval Strike Aircraft Test Squadron in Patuxent River, Maryland as F/A-18E/F Super Hornet Lead Carrier Suitability Test Pilot. He returned to the fleet in VFA-34 stationed at Virginia Beach, Virginia and deployed aboard USS GEORGE WASHINGTON.

He has accumulated over 3300 flight hours in 30 types of aircraft and 608 arrested landings. He flew 67 missions over Iraq and Bosnia-Herzegovina/Kosovo in support of Operations SOUTHERN WATCH and DELIBERATE FORGE.

He is currently a Senior Experimental Test Pilot with The Boeing Company.